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Virtual Battle Experiment AS-4: Explorations of Networked Maritime Operations

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ABSTRACT

This report provides a summary of Virtual Battle Experiment-AS4 held at DSTO-Edinburgh in August 2003 in support of TTCP MAR TP-1 (Command, Control and Information Management). The study was designed to investigate possible picture compilation benefits provided by a maritime tactical network. Novel human-in-the-loop simulation methodology was employed in which a networked virtual submarine undertook a surveillance patrol with track information fed to three separate Track Managers. Data analyses compared resulting picture quality and human performance. The findings of the study were that networking assisted picture completeness and detection continuity at the cost of higher operator workload

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Virtual Battle Experiment AS-4: Explorations of Networked Maritime Operations

Executive Summary

This document presents an overview of a study entitled Virtual Battle Experiment-Australia 4 (VBE AS-4). The study was conducted in August 2003. VBE is the name given to a series of such studies being carried out as part of a collaborative programme within The Technical Cooperation Program (TTCP) Maritime (MAR) Technical Panel (TP) 1 (Maritime Command, Control and Information Management).

The purpose of the VBE series has been to investigate potential picture compilation benefits provided by networking within the maritime domain. VBEs involve immersion of human participants within a realistic synthetic environment, providing them with a suite of tactical applications and observing picture compilation in detail. The VBE concept required that this simulation capability be provided by a common environment, which could be integrated with national applications and systems in any country. It was also required that the simulation have the flexibility to allow individual countries to develop and integrate their own models. The Virtual Maritime Systems Architecture (VMSA), developed by DSTO, was chosen to support this environment. The VMSA also supports software such as ownship helm control to allow the virtual platforms hosting these applications to dynamically interact with the synthetic environment. High level objectives for the sequence of VBEs are many. They include:

1. Provide a framework to quantify the impact of a Network Enabled Capability.
2. Examine types of information to be exchanged between coalition partners.
3. Measure the picture compilation benefits.
4. Develop and assess different concepts related to picture compilation within a Network Enabled Capability. These concepts can cover anything from methodologies for Track Number allocation through to command team interactions.
5. Investigate human factors issues related to a Network Enabled Capability.
6. Demonstrate these benefits and concepts to the stakeholder community.
7. De-risk Network Centric Warfare (NCW) related technology prior to transitioning to sea trials.
8. Help direct future research and identify exploitation routes through to the fleet.

The first VBE (VBE-A) was held in the UK in May 2002: primarily an integration exercise to demonstrate that the physical architecture proposed for VBEs was appropriate. Since VBE-A a number of studies have been held in support of both collaborative experimentation within TTCP and individual research programmes. As such, an objective of the present experiment was the further development and demonstration of the infrastructure and experimental conduct required to facilitate future VBEs in support of individual national programmes. Secondary objectives of VBE AS-4 were to examine three

simple NCW related hypotheses. These, introduced later, provide the major focus of this report. A novel concept that has been termed 'Concurrent Comparison' was developed to allow us to comment on the hypotheses examined. This method has not yet been developed to the extent that would enable inferential hypothesis testing however. Therefore the present study should be considered exploratory.

The scenario used for the study involved four coalition platforms. Ownship (a virtual submarine) was required to undertake covert surveillance of an area where hostile vessels were expected to be transiting in addition to local merchant and fishing traffic. The other coalition platforms were two frigates and an unmanned air vehicle which were all able to transmit tactical track data to ownship. The scenario was entirely scripted with the exception of the virtual submarine.

In terms of picture quality, VBE AS-4 supported the view that sharing of track information between coalition partners allows individual platforms to maintain a more complete representation of the environment. However it was not possible to explore whether this more complete picture provided any benefit in achieving the overall operational objective. This is likely to be an ongoing issue for some time with VBEs, in that it is perfectly feasible to measure improvements in the overall tactical picture provided by networking, but how this relates to overall mission effectiveness is considerably more difficult to ascertain.

Authors

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Dr. Sam Huf joined DSTO in 1999 from James Cook University. Until mid 2002 he worked for DSTO's Land Operations Division in Human Systems Integration. Since then his work has involved human factors analyses of Australia's Collins class submarine combat system and Maritime simulation experimentation. His overarching interest is in coevolution of information technology and human command systems. Sam completed a BPsych(Hons) and a PhD in Visual Perception through James Cook University.

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Dr. Rodger Manning is a UK scientist from QinetiQ on attachment to the Submarine Combat Systems Group within Maritime Operations Division at the time of writing. Within QinetiQ he is a Technical Leader responsible for establishing the direction of sonar data processing and submarine combat system research in response to the future capability requirements of UK MOD. He is also currently responsible for the management of the Virtual Battle Experiments within SMCS in support of TTCP and AAMOUR collaboration projects.

Dr. Rodger Manning completed a Ph.D. in Physics at the University of Birmingham, UK in 1994 following a B.Sc.(Hons.) in Physics with Astrophysics from the same university. He joined DRA as a Higher Scientific Officer in 1995, became a Senior Scientific Officer within DERA in 1997 before his current promotion to Technical Leader within QinetiQ in 1999.

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Dr. Sanjeev Arulampalam received the B.Sc. degree in Mathematics and the B.E. degree with first class honours in Electrical and Electronic Engineering from the University of Adelaide in 1991 and 1992, respectively. In 1993, he won a Telstra Research Labs Postgraduate Fellowship award to work toward a Ph.D. degree in Electrical and Electronic Engineering at the University of

Melbourne, which he completed in 1997. His doctoral dissertation was in the area of Hidden Markov Model based tracking algorithms. Upon completion of his postgraduate studies, in 1998 Dr. Arulampalam joined the Defence Science and Technology Organisation (DSTO), Australia, as a Research Scientist in the Surveillance Systems Division. Here he carried out research in many aspects of target tracking with a particular emphasis on non-linear/non-Gaussian tracking problems. In March 2000, he won the Anglo-Australian Postdoctoral Research Fellowship, awarded by the Royal Academy of Engineering, London. This postdoctoral research was carried out in the U.K, both at the Defence Evaluation and Research Agency (DERA) and at Cambridge University, where he worked on Particle filters for nonlinear tracking problems. Currently, he is a Senior Research Scientist in the Submarine Combat Systems group of Maritime Operations Division, DSTO, Australia. His research interests include estimation theory, target tracking and Sequential Monte-Carlo methods.

Contents

1. Introduction

1.1 Overview

This document presents a study of the impact of networking a conventional submarine with vessels within a coalition vessel grouping. The study was entitled Virtual Battle Experiment (VBE) Australia (AS)-4. It was conducted August 5, 2003, DSTO Edinburgh, Australia. The name VBE refers to a series of experiments being undertaken both within Maritime Operations Division (MOD) DSTO, and The Technical Cooperation Programme Maritime Technical Panel –1 (Maritime Command, Control and Information Management). The purpose of these experiments is to investigate and quantify the possible benefits to be gained by the sharing of tactical information via coalition data networks, that is, by implementing network enabled maritime operations of the type likely to emerge in an era of Network Centric Warfare (NCW). A detailed discussion of the utility of the NCW concept is beyond the scope of this paper. The paper addresses a specific implementation of the general NCW concept that involves sharing of tactical track level data in real-time between Naval task group elements.

Within VBEs, human participants are immersed in, and interact with, a computer-generated environment. They are provided with a suite of tactical and track management applications and are able to manoeuvre their virtual platform through computer-generated water space. The scope of VBEs can be targeted to specific aspects of combat system functionality or broader tactical issues. It is intended that the VBE concept will allow assessment of individual components or the capture of complex interactions that occur onboard real platforms [1, 2].

A Virtual Maritime Systems Architecture (VMSA) [3], developed by DSTO, provides the synthetic environment. Software such as ownship helm control can also be provided to allow the virtual platform hosting these applications to interact with the computer-generated environment. Virtual platforms are provided with a sensor suite to simulate interaction with real world objects.

The VBEs focus on the applications, algorithms and information exchange requirements that might support picture compilation within a network enabled coalition as a simple approximation of an NCW relevant operation - rather than the physical communication infrastructure *per se*.

High level objectives for the programme of VBEs included [1, 2]:

- Provide a framework to quantify the impact of a network capability.
- Examine types of information to be exchanged between coalition partners.
- Measure the picture compilation benefits.
- Develop and assess different concepts related to picture compilation within a Network Enabled operation. These concepts can cover anything from methodologies for Track ID allocation through to command team interactions.
- Investigate human factors issues related to NCW.
- Demonstrate these concepts to the stakeholder community.
- Help direct future research and identify exploitation routes through to the fleet.

These last two points are particularly important. Although the transitioning of research output through to equipment procurement programmes is rarely straightforward, the complex domain of NCW can make this process especially difficult. This is primarily because of the multifaceted interactions between the various components that can contribute towards effective network enabling of combat systems (and likewise its failure). For example, it is not easy to quantify or demonstrate in isolation the overall operational benefit of a particular application designed to support NCW. However it is believed that VBEs have the potential to assist greatly in minimising the risks that may arise in attempting to introduce technologies into Network Enabled (NE) operations. Experimentation such as these VBEs can make important contributions at all stages of the acquisition cycle.

A summary of the VBEs that have been held to date is provided in Table 1. The first VBE (VBE-A) was held in the UK in May 2002. This VBE was primarily an integration exercise to demonstrate that the physical architecture proposed for VBEs was appropriate. Since VBE-A a number of VBEs have been held in support of both collaborative experimentation within TTCP and individual countries' research programmes.

Table 1 VBE[1] Studies to Date

VBE	*Date*	*Location*	*Scenario*	*Principal Objectives*
VBE-A	May 2002	UK	2 platform coalition (ASW)	VMSA connectivity verification.
VBE-AS1	Oct 2002	AS	2 platform coalition (ASW)	Develop baseline methodology and infrastructure for VBEs.
VBE-AS2	Dec 2002	AS	2 platform coalition (ASW)	Introduction of non-scripted ownship. Development and use of metrics for detailed analysis.
VBE-AS3	May 2003	AS	4 platform coalition (ASuW)	Define infrastructure baseline for VBE-B.
VBE-B	May 2003	NZ	4 platform coalition (ASuW)	First full five nation VBE.
VBE AS-4	August 2003	AS	4 platform coalition (ASuW)	Define performance baseline for future VBEs.

1.2 Objectives of VBE AS-4

An overarching objective of VBE AS-4 was to continue development and demonstration of the infrastructure and experimental conduct required to facilitate future VBEs in support of

[1] The naming convention for VBEs is that those studies held by an individual nation are identified by an appropriate two letter country code followed by an incrementing number. An incrementing letter identifies those held as a collaborative experiment.

individual national programmes. More specifically, three hypotheses exploring NCW were identified for investigation. These were:

1. IF track sharing occurs THEN a more complete and accurate representation of the operating environment can be maintained by each platform.
2. IF track sharing of high priority targets occurs THEN they can be more continuously monitored with a greater accuracy.
3. IF shared tracks have a realistic Area of Uncertainty THEN command will have a greater trust in the information and will associate and fuse them more readily with own ship tracks.

These hypotheses address the most basic characteristics of NCW operations, that is, that in receiving sensor data or tracks from coalition vessels, networked vessels will have access to an expanded field of view of the tactical situation. No one experiment will prove or disprove the utility of NCW concepts, but testing hypotheses such as these explores practical issues that will need to be addressed. In addition to these specific points a number of other technical, human and operational factors were observed. These observations were intended to gain a general insight into aspects of NCW operations to be researched in future.

2. VBE AS-4 Summary

2.1 Scenario Overview

The scenario for VBE AS-4 was developed to provide a realistic low-tempo setting (see Figure 1).

For VBE AS-4 (and all previous VBEs to date) the movement of individual platforms was entirely scripted with the exception of ownship - a simulated submarine (called HMAS vWaller). HMAS vWaller had its initial course, speed and depth pre-defined, after which, the Commanding Officer (CO) was responsible for its manoeuvres. The scenario was designed to last up to five hours. vWaller was crewed by a team of control room operators performing roles typical at sea. These roles will be discussed in later sections.

The scripted scenario was generated using the Scenario Generator developed by Defence Research and Development Canada, which creates a script file that can be read by the gameboard controller within VMS).

2.2 Scenario Background

The following context was provided to the control room team of vWaller:

"Intelligence indicates that a country to the north of a coalition partner has been steadily increasing the size of its armed forces, with the intention of expanding its borders to incorporate the northern area of the coalition. While hostilities have not been declared the Coalition Governments wish to prepare for a pre-emptive strike in case the situation

deteriorates to an unacceptable level. This possible strike will be in the form of an amphibious landing. However there is little knowledge of the area, and how well fortified the area might be. Therefore HMAS vWaller has been tasked to conduct surveillance and reconnaissance, prior to the arrival of the task group.

The opposition controls sea and air space out to a range of 40 NM from his coastline. HMAS vWaller is to conduct a covert patrol, within the 40 NM zone, and establish the tactical environment prior to the task force arriving. Of particular interest is any movement of military shipping within the local area. There are two coalition vessels operating in the area. The first (FFH1) is approximately 80 NM to the northeast and is preparing to deploy an Unmanned Airborne Vehicle (UAV) to search the area to the south east of HMAS vWaller. The second (FFH2) is operating approximately 80 NM to the northwest and is conducting a surface search. North of the current position of HMAS vWaller there is a shipping lane running northwest to southeast, and to the south west there are fishing grounds."

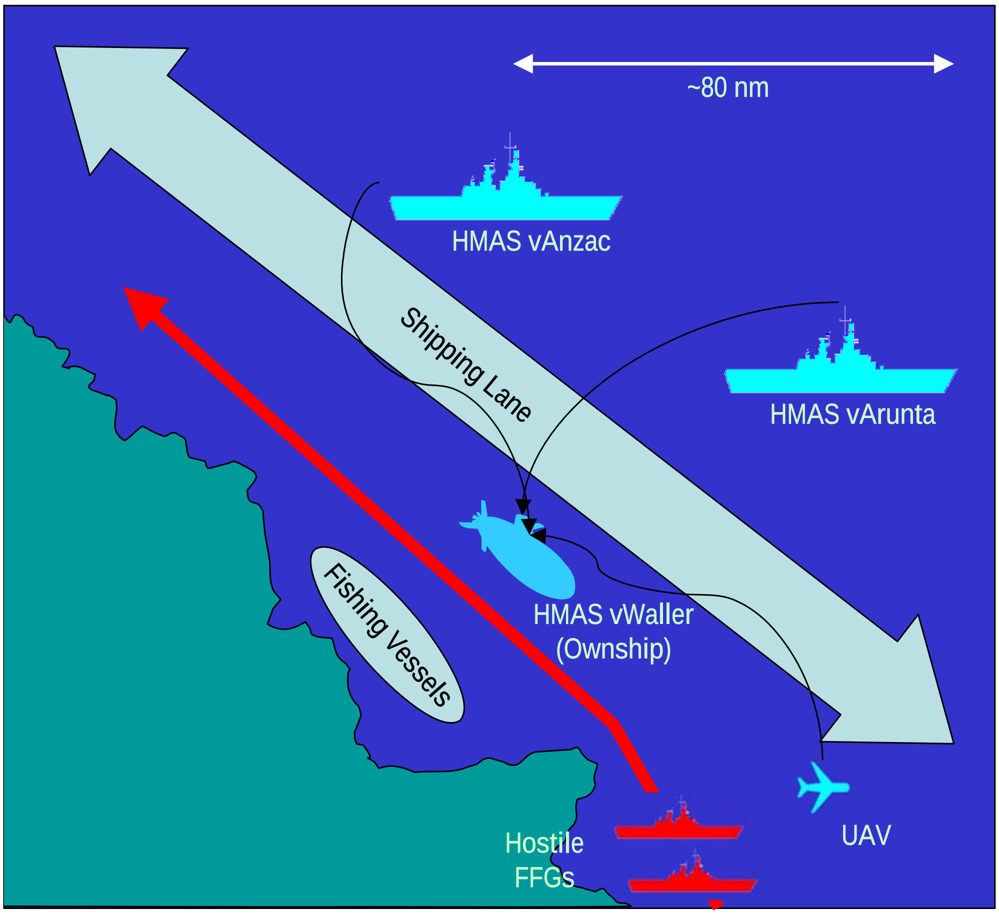


Figure 1 VBE AS-4 Scenario Overview

2.3 Sensor Fits

The sensor fits for the various platforms, along with their nominal detection ranges are summarised in Table 2.

Table 2 VBE AS-4 sensor fit

Platform	*Sensor*	*Detection range (nautical miles)*	*Detection Range (km)*
HMAS vWaller	Sonar	10	18.5
	ESM	20	37.0
HMAS vARUNTA (FFH 1)	Radar	60	111.0
HMAS vANZAC (FFH2)	Radar	60	111.0
UAV	Radar	30	55.5
	EO	10	18.5

2.4 Coalition Information Exchange

All radar tracks held by the two coalition frigates were communicated to ownship: vWaller. These tracks were assigned a classification of air / surface entity with an unknown hostility.

All radar tracks and visual reports from the UAV were communicated to vWaller. If only a radar track was held then this was assigned a classification of air / surface entity with an unknown hostility. Once the contact had been detected visually the known hostility was assigned to both the visual and radar tracks.

2.5 HMAS vWaller Tasking

HMAS vWaller was tasked to conduct a surveillance patrol within 40 NM of the coastline and monitor for Indications and Warnings of hostile intent, prior to the arrival of the Coalition Amphibious Task Group.

The priorities for HMAS vWaller were:

1. *Remain undetected.*
2. *Establish surface/subsurface/air activity.*
3. *Locate and track military shipping.*

The Rules of Engagement were:

1. *You may engage the enemy only in self-defence.*
2. *You are not to intentionally close any unit to within 8 kyds as this may be viewed as a hostile act.*

2.6 Picture Compilation Task

A major role of the submarine "Command Team" (stationed in the control room) is to build an accurate picture of the world around them. This is referred to as picture compilation. Ground Truth tracks stored during the scenario provide a comparison against which the tactical picture compiled by human operators and or automated tools, during the VBE, can be directly compared. A simplified activity diagram of current picture compilation activities, as observed at sea, is shown in Figure 2.

The current estimated range, course and speed of a contact is referred to as its *solution*. Situational or characteristic clues provided from sonar, visual, radar or electronic support measures (ESM) constrains the uncertainty surrounding the achievement of a solution. Track Management (TM) and Target Motion Analysis (TMA) is an iterative process that is conducted on every contact to refine a Range, Course and Speed solution (addressed in detail later). Once a solution has been assigned it is monitored constantly in reference to the Contact Evaluation Plot (CEP).

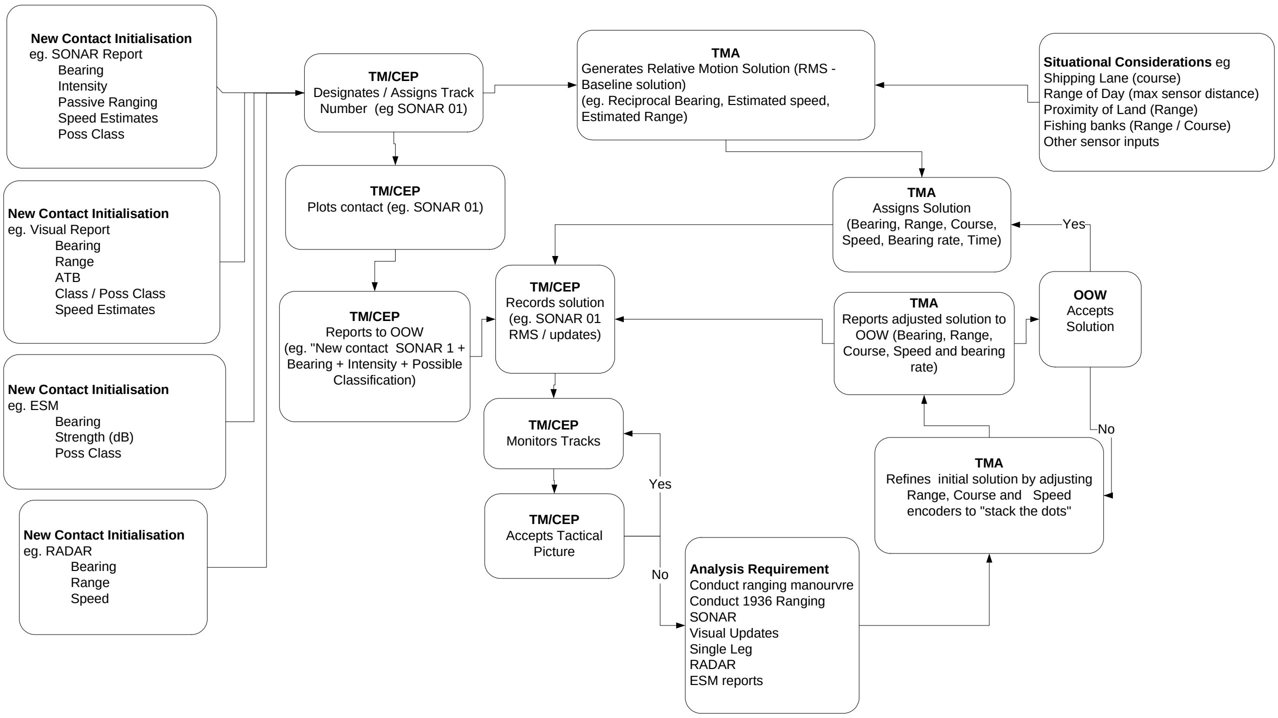


Figure 2 Basic Picture Compilation Process [4]

3. Infrastructure

3.1 Overview

This section reviews the infrastructure implemented for VBE AS-4, and includes a description of the simulation environment, applications, major data flows between the principal components and display layout.

A high level representation of the infrastructure for VBE AS-4 is shown in Figure 3.

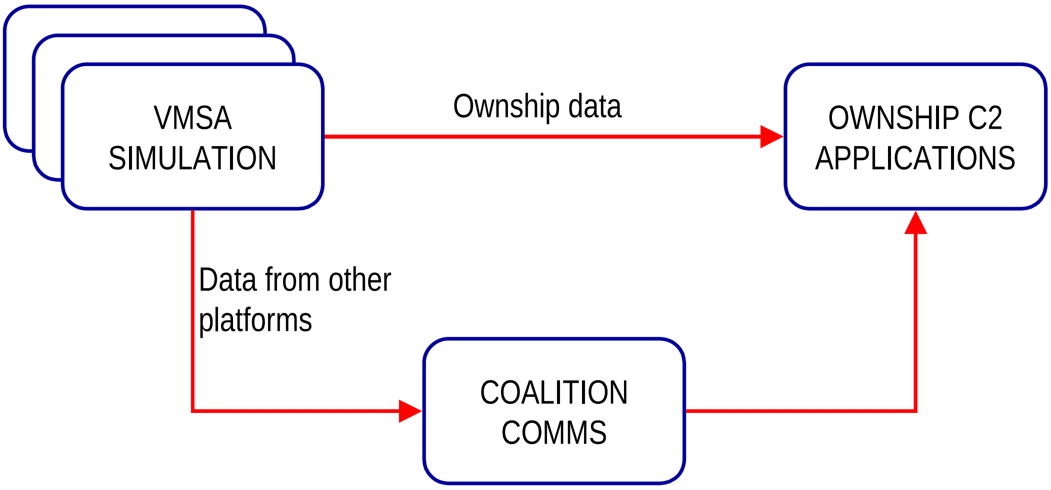


Figure 3 High level view of infrastructure for VBE AS-4.

The actual VMSA simulation environment modelled kinematic data of all platforms within the scenario as well as track data arising from all coalition sensors that were present. Ownship C2 applications within vWaller received data corresponding to its own sensors direct from the simulation. However track data from the coalition platforms was transmitted via dedicated TCP / IP links. Although this data could be passed directly to ownship within the simulation, the use of an external communication route is preferred within VBEs because it allows different NCW communication methods and protocols to be investigated. It will also more readily support the modelling of communication bearers within future VBEs. A VBE communications protocol manipulation concept is under development to simulate possible architectural characteristics but was not implemented in VBE AS-4.

The Infrastructure includes a set of software models termed 'federate', whose outputs simulate activities real world objects (RWO) in a simple tactical setting (see Table 3).

Table 3 Virtual Maritime System Architecture Federate Components

1. Visual Reporting Federate	Simulates manual visual reports from a surveillance aircraft. Following first detection the "observer" waits until the aircraft has passed the closest point of approach. A fix is then taken and track reported. After processing other visible platforms are reported. For each contact, relative bearing, range along with estimates of course and speed are reported. An Area Of Uncertainty, for each contact, is defined as an ellipse whose major and minor axes correspond to a bearing error of +/- 2^o and a range error of +/- 25%. Estimates of elevation, course and speed are also provided with errors of +/- 6^o, +/- 22.5^o and +/- 25% respectively.
2. Motion Federate	A generic motion federate used to model the motion of simulated sea-based platforms using realistic acceleration, turn and dive rates.
3. UAV/Surveillance Aircraft Federate	A surveillance aircraft federate that provides aircraft kinematic modelling. In the future it is hoped to link this federate to a commercial flight simulator to provide both dynamic and realistic aircraft modelling.
4. Navigation Federate	A generic navigation federate used to model the navigation capability of simulated platforms. For VBE-B the navigation federate was simply a replication of ground truth. However the federate will allow the impact of the performance of the navigation systems to be investigated in future VBEs.

3.2 Ownship C2 Applications

3.2.1 Horizon 3 Overview:

Horizon 3 [see 5], facilitates management of track data within the vWaller control room. Central to Horizon 3 is the use of custom plugins to ease the introduction of third party applications and allow configuration changes to match varying user requirements (see Figure 4).

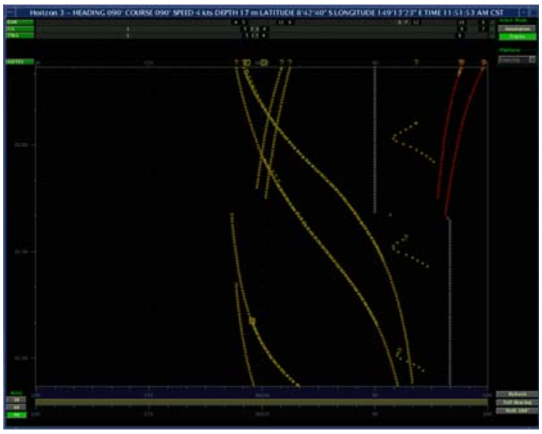
Horizon is a developmental software tool under constant revision depending on the requirements of experimentation and the task of the operator. In VBE AS-4, the Horizon 3 user interface employed a situation plan view (called a Tactical Picture Display – TPD – See Figure 4a), together with a set of interaction tools such as zoom, track filtering, annotation, shoreline overlay and cursor position readouts (see [5] for details). The map display also has an 'off-platform' mode to facilitate the manual cross-fixing of bearing reports from sensors located in different positions, including own-ship and coalition members. In addition, the operator was able to switch to a Time Bearing Display (Figure 4b) to observe the change in relative bearing (bearing relative to ownship heading). Further, Horizon 3 also provided an interface (see Figure 4c) suitable for simulation of the sensor suite (sonar, ESM and Periscope).

3.2.2 Horizon 3 Functionality: Track Management

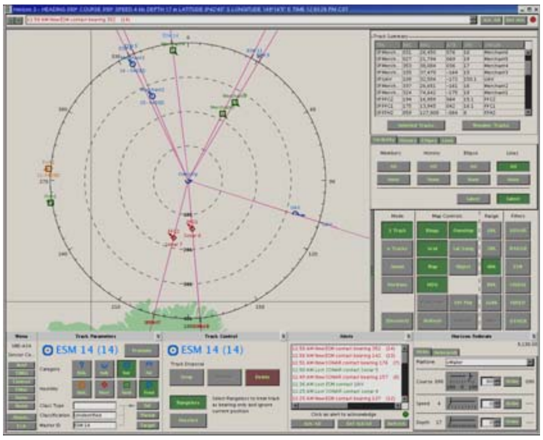
Track management functionality incorporated within Horizon 3 included manual classification assignment, track dropping and deletion, track "promotion" to other Horizon displays, track association and fusion.

In addition to allowing operators to select tracks for association and fusion using an entirely manual process, the release of Horizon 3 used for VBE AS-4 incorporated a basic nearest neighbour algorithm. This algorithm provided recommended actions, i.e. track association or disassociation recommendations according to track data covariance. The algorithm (see [5] for details) is based upon a "bearings-only" gating technique.

a. Typical Tactical Display (TPD)



b. Time Bearing Display



c. "God's Eye View" (Sensor Controller Operations)

Figure 4 Horizon 3 displays derived from VBE AS-4: Horizon situation display

Operators were able to fuse tracks by selecting an appropriate fusion algorithm. Figure 5 demonstrates the resultant outcome of Track fusion. In Figure 5a tracks T_1, T_2 and T_3 are fused to yield T_4. Hence, fusion involves "association" or grouping of two or more component "track" segments that are attributable to the same RWO but from different sonar arrays. The examples in Figure 5 refer to the association of tracks derived from Flank and Towed arrays. Fusion can be handled in many different ways. Several examples presented in Figure 5 are as follows:

i. Preferred Sensor

For the Preferred Sensor algorithm the operator was able to assign a preferred priority order for the sensors from which associated tracks were derived (e.g. Flank Array or Towed Sonar Arrays). Figure 5b demonstrates an instance where Towed Array was selected as "Preferred Sensor".

ii. Hide Others
The Hide Others algorithm was similar to the Preferred Sensor algorithm; except that *only* track data from the most preferred sensor was used. Note, however, that if this track is subsequently dropped then its history is not updated until there are more data from this sensor. This is shown in Figure 5c where the fused track T_4 follows the Towed Array tracks, T_1 and T_2 , and the Flank Array Track T_3 is ignored or "hidden".

iii. Join
The Join algorithm was used to associate temporally disjoint tracks. This algorithm operates so that, when member tracks within a fused track are concurrent, fused track attributes do not change until one member track is dropped. This is demonstrated in Figure 5d. Here, in a similar manner to the Preferred sensor order algorithm, Towed Array Tracks T_1 and T_2 and effectively combined with the Flank Array track T_3 when Towed Array tracks are dropped. The difference being that component tracks (T_1, T_2, T_3) are temporally disjoint (at t_1 and t_2). The association at Figure 5d yields fused track T_4 .

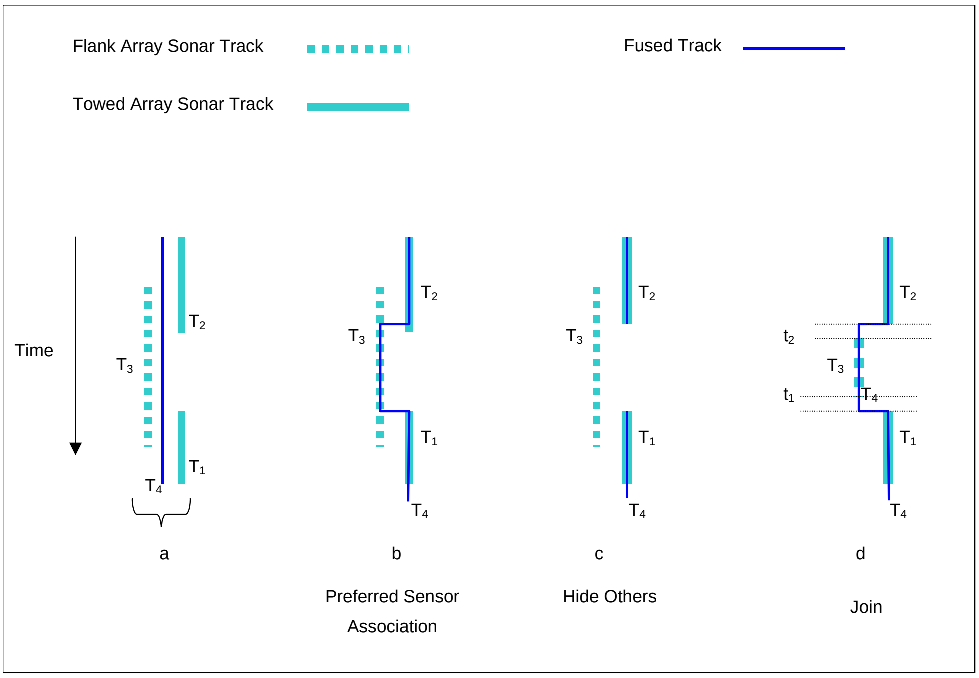


Figure 5 Preferred Sensor, Hide Others and Join track fusion algorithms

Other more complex algorithms included (detailed discussion is beyond the scope of this general document):

iv. Extended Kalman Filter
The Extended Kalman Filter fusion algorithm used bearing data relative to the individual sensors in order to estimate the kinematic characteristics for a fused track.

v. Closest to Source
The Closest to Source algorithm required at least one of the member tracks of a fused track to have a position solution. The member track with a position closest to the appropriate sensor position is used for the fused track attributes.

3.3 Target Motion Analysis

Target Motion Analysis is a crucial part of the overall picture compilation and track management process. In VBE AS-4, TMA was performed using the tool ITMA, where a display of residual error in a series of range, course and speed solutions is analysed graphically (by means of an interactive visualisation). The tool simulates manual TMA undertaken at sea where a series of "dots" (representing a sequence of solutions over time) are "stacked" in a straight line by manipulating the range, course and speed of a particular contact. A set of "stacked dots" is achieved when the solution best fits the geometry of a contact's motion over time (range, course and speed relative to ownship – see Figure 6). ITMA is a DSTO developed display and analysis tool based closely on equivalent devices employed at sea.

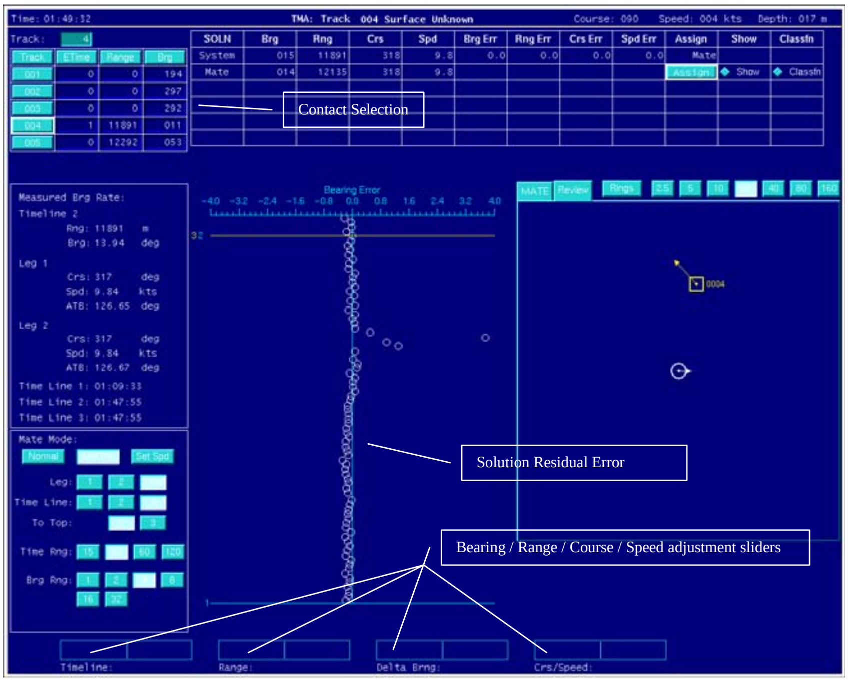


Figure 6 TMA Display (ITMA)

3.4 Coalition Communication Mechanism

3.4.1 Horizon Promotion Communication

Horizon Promotion Communication has been used in every VBE to date (barring VBE-AS1). It is a TCP/IP based communications method adopted to enable physically distributed instances

of Horizon and other applications to share track and navigational information. Within Horizon only those tracks that are labelled for promotion are distributed. This process of promotion can either be manually or automatically initiated.

All messages are prefixed by a 'Message Header' that indicates why it has been sent followed by an appropriate number of records each with its own separate header as shown in Figure 7.

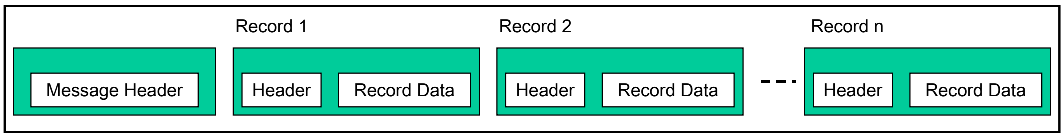


Figure 7 Message and record concept for Horizon promotion communication

The possible message reasons that are currently implemented are:

- A shutdown request and that the client should not attempt to reconnect.
- Initialisation.
- A track has been created within the server's repository.
- A track has been promoted from the server's repository.
- Track data for a promoted track, other than solution data, has been modified.
- Solution track data for promoted tracks has been modified.
- A new source platform (i.e. a coalition vessel) has been created.
- A source platform has been deleted.
- Kinematic source platform data has been created.
- A track has been demoted
- Track association changes

There are currently six different record types that have been developed for use with Horizon Promotion Communications:

- Track details other than solution related data
- Track Number
- Track solution data (e.g. bearing, range, course etc.)
- Source platform details
- Source platform history
- Track association changes

3.5 Summary Data Flows and Display Layout

3.5.1 Data Flows

In VBE AS-4 the control room of vWaller was simulated using a set of displays that enabled comparison of operator activity. A high level functional diagram of the major ownship data flows is shown in Figure 8 below. Four roles were played. The roles wer: three track manager roles plus a human-operated TMA role supporting ownship track management (as in current practice).

Data flows and display layout enabled comparison of picture compilation undertaken using current practices (detection, localisation and tracking using ownship processing) against a network enabled process (sensor data available from coalition vessels). Note that data from coalition vessels was input to the networked displays subsequent to refinement of individual track solutions performed by manual TMA upon ownship detected tracks.

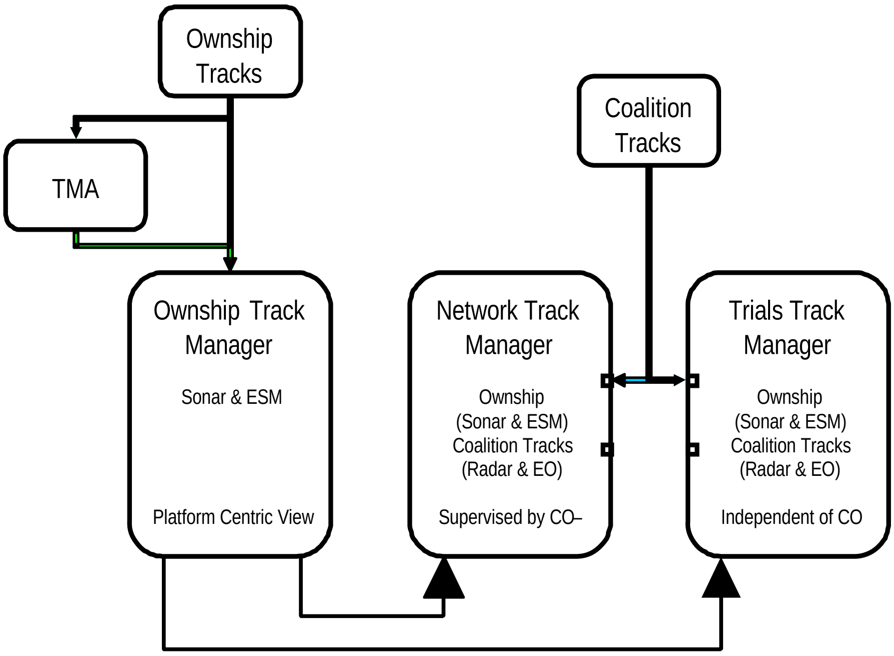


Figure 8 VBE AS-4 Data Flows

The major roles identified above are addressed briefly in Table 4 (and described in some detail later).

Table 4 Operator roles in the vWaller control room

Title	**Task**
Ownship Track Manager (OSTM)	Management of tracks resulting from simulation of Ownship sonar and ESM sensor detections at typical ranges.
Network Track Manager (Net TM)	Management of tracks resulting from Coalition sensors as well as those resulting from Ownship sonar and ESM sensors in addition at typical ranges (supervised by CO)
Trials Track Manager (Trials TM)	Management of tracks resulting from Coalition sensors as well as those resulting from Ownship sonar and ESM sensors in addition at typical ranges (unsupervised track management – employing augmented track management techniques)
Target Motion Analysis (TMA) – supports OSTM Role	Utilised DSTOs custom operator supported TMA tool ITMA, to refine the range, course and speed solution on individual tracks (employs contextual information).

3.5.2 Display Layout

In terms of the Track Management as part of Picture Compilation activities, each operator was supplied with two displays (see Figure 9 below). One display was meant to be used as a "work bench" at which tracks were identified and compared and if possible fused to integrate the tactical picture. The idea was that the operator would promote those tracks that were thought to be valid associations (or valid unassociated tracks) to a Tactical Picture Display (TPD). Hence each Track Manager had an associated TPD display (as in Figure 9). Information on the character of vessels being tracked (eg. Classification by acoustic properties, best speed by sonar, visual contact and radar analysis) were supplied verbally by a sensor controller[2] (see 4.1.3 for details on this role).

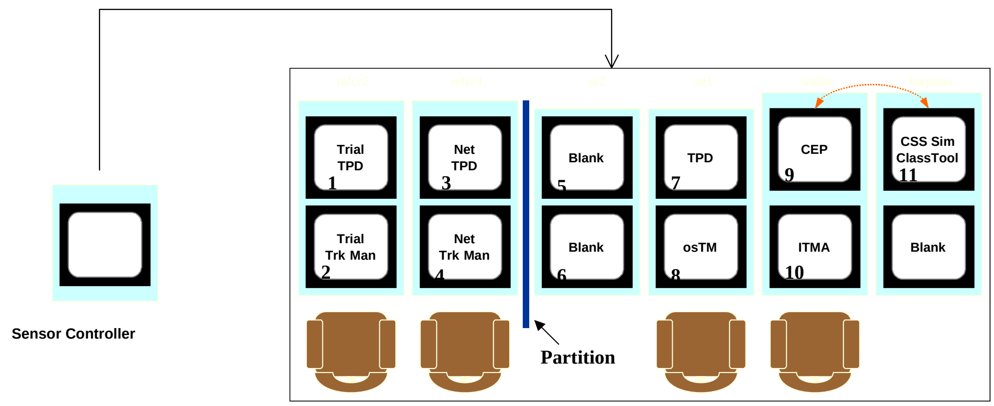


Figure 9 Ownship Display Layout

3.6 Location and Physical Environment

VBE AS-4 was undertaken at MOD, DSTO undersea battle lab (see Figure 10 below). Lighting, screen layout and screen luminance are set to approximate conditions experienced at sea. However, in an effort to support the CO situation awareness, standard screen displays were projected at a large scale as shown in the Figure.

[2] This role has been found, in previous studies, to be crucial to the task of tracking. It provides the human operator with a picture of the possible real world constraints that exist around constructed entities thus constraining the task of bearing only tracking generally and TMA in particular.

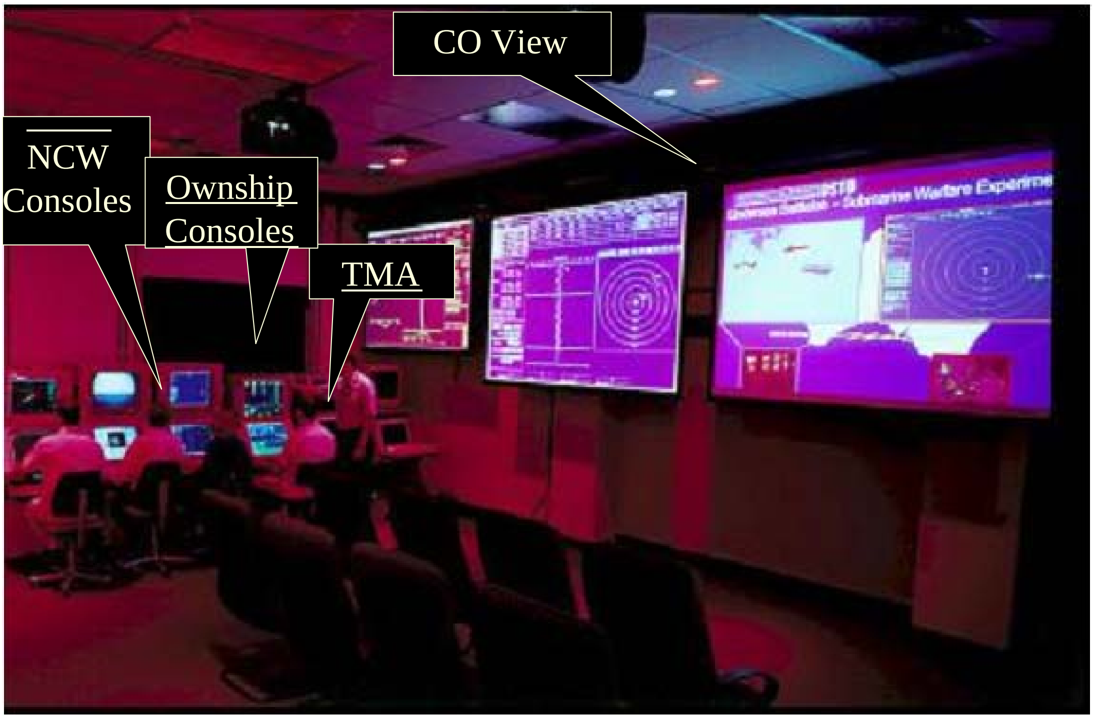


Figure 10 MOD's Under Sea Battle Lab

4. Experimental Conduct

4.1 Participants

All but one of the operator positions played out during VBE AS-4 involved experienced RAN personnel. Although TMA was undertaken by civilians they were experienced with TMA and the use of the software. The crewing of the vWaller command team is summarised within Table 5. Their roles are addressed below.

Table 5, Crewing for VBE AS-4

Role	*Organisation*
Commanding Officer	RAN Reserve
Ownship Track Manager	RAN
Sensor Controller	RAN
Target Motion Analysis	DSTO (experienced)
Network Track Manager	RAN
Trials TM	RAN

4.1.1 Commanding Officer

The CO had overall responsibility for vWaller. For the purposes of this experiment his two principal tasks were the manoeuvring of vWaller and the development of the tactical picture in accordance with the platform's tasking. To assist him in this process he was provided with

plan displays of coalition only data (Horizon – coalition console) and ownship only data (Horizon – TPD console).

4.1.2 Ownship Track Manager (OS TM)

The OS TM displays were provided with track data direct from vWaller's onboard sensor models (Sonar and ESM). These contacts were required to be classified and a solution refined in the TMA process. The CO worked with the ownship track manager who he directed on which tracks he would like fused and when. The CO also was able to instruct the OS TM on which tracks he would like promoted to his command display (Horizon – command console). This provided him with an uncluttered display of the key information contained within the OS TM display (Horizon – track manager console).

4.1.3 Target Motion Analysis (TMA)

TMA is used by submarines to refine localisation of contacts. While it is recognised that TMA at sea is a broad concept involving several possible inputs, in this paper, TMA refers only to the digitised processing of track information with operator support. The operator becomes directly involved in the TMA process by editing the data used, merging information from different sensors (eg. cylindrical arrays and distributed array), applying constraints (eg sensible kinematic course, or range restrictions) or using manual techniques.

Manual TMA allows the operator to adjust the solution parameters and to observe the effect on the error residuals. This manual approach to TMA, whilst operator intensive, is useful in situations where geometry and data quality can cause automatic TMA algorithms to degrade.

4.1.4 Network Track Manager (Net TM)

The Net TM console received track data from ownship sensors (sonar and ESM) and from the coalition partners. He then assisted the CO in developing the tactical picture through providing recommendations for fusion and undertaking any fusion instructions. He also assigned classifications and promoted tracks to the Command display as directed by the CO. The Net TM was permitted to provide guidance to the trials operator as long as it did not impact on his own tasks.

4.1.5 Sensor Controller

This operator was provided with a Horizon system that provided a labelled plan display of the ground truth that was not visible to the rest of the vWaller team. This system also displayed the tracks that were currently held by ownship sensors and the RWOs to which they corresponded. Using this the Sensor Controller was able to provide estimates of the information that is typically expected from sonar, periscope and ESM departments. Examples of this type of information are range by DA (Distributed Array), classification, and best speed by sonar. The sensor coordinator was also responsible for operating the helm as directed by the CO.

4.1.6 Trials Track Manager (Trials TM)

The Trials TM was given the freedom to act completely independently of the CO and develop his own tactical display based upon ownship tracks (sonar and ESM) and the tracks sent over from coalition. The Trials Manager was allowed to fuse any tracks of her choosing, when she wanted and using the algorithms (see Fig. 5) of her choice. This role was introduced to provide a comparison with the current practice of the CO (or Officer of the Watch) having responsibility for the fusion of external tracks with those from ownship. The Trials Manager was also requested to make recommendations to the Track Manager.

4.1.7 Track Fusion Procedures

The CO, Net TM and Trials TM were provided with the following instructions on which algorithm to use when fusing tracks together.

1. If two or more of the tracks to be fused have a position solution then the preferred order for the fusion algorithms is:

    i. Extended Kalman Filter (EKF)
    ii. Preferred Sensor
    iii. Closest to source

2. If an ownship sonar or ESM bearing track is to be fused with one or more coalition tracks then the preferred order for the fusion algorithms is:

    i. EKF
    ii. Preferred Sensor (probably set to one of the coalition tracks)
    iii. Closest to source

3. If ownship tracks only are to be fused then the preferred order for the fusion algorithms is:
    i. Preferred Sensor
    ii. EKF

4.2 Analysis Summary: Series Comparisons

The above arrangement of operators and displays enabled comparison of the *current process* of picture compilation to be compared with future NCW-like *picture compilation.*
Current practice essentially provided a baseline against which a NCW environment could be compared. For this study the baseline was the tactical picture compiled by vWaller independent of the coalition (where Track Manager extracts tracks from sonar and ESM detections and the corresponding TMA solutions).

In summary current process was represented by providing simulated organic sonar detection data to a conventional Track Manager working together with a Target Motion Analyst to compile the tactical picture.

NCW operations were represented by

Net TM: This operator was supervised by the CO and was supplied the output of the OS TM (organic sensors as in current practice) together with contact data supplied by coalition vessels (including a UAV).

Trials TM: supplied the output of OS TM but provided with a suite of algorithms and given licence to exploit the networked information.

4.3 Observers

VBEs require a number of formal observer roles. These are given in Table 6.

Table 6, VBE AS-4 Observers

1. VMSA Observer	The VMSA observer ensured that the simulation was running as expected. Any peculiarities observed that whilst not halting the conduct of the experiment may impact on subsequent analysis or future VBEs were to be reported.
2. Infrastructure Observer	The infrastructure observer ensured that all the applications and supporting infrastructure were operating as expected and that all the required data flows were in place.
3. Conduct Observer	The conduct observer monitored the overall conduct of the experiment and identified key moments within the experiment and important issues associated with the performance of the team from a human factors perspective. The conduct observer also maintained an informal log of the experiment.
4. Horizon Observer	The Horizon observer monitored the overall performance of Horizon, and identified any issues associated with the use of this application with particular attention paid to its operability and algorithm performance. Aspects of the HCI that the operators found difficult to use, or used in a different way from that intended were also noted.
5. Photographer	Responsible for creating a photographic and video record before during and after the conduct of the experiment.
6. Coordinator	The coordinator had overall responsibility for ensuring that the experiment was conducted in a manner as specified in experimental plan or as could best be achieved whilst still supporting the objectives of the experiment.

4.4 Workload Monitoring and Situation Awareness

4.4.1 Workload

Data overload is often discussed as a possible risk for NCW capability. The human operator is vulnerable to information flooding. However, cognitive workload in particular is not an easy thing to measure. Measures of workload are typically survey instruments such as NASA's Task Load indeX (NASA TLX).

Such surveys are most often given after the completion of a task. In a wargame scenario it was anticipated that workload would increase and decrease dramatically so it was decided to trial a very simple moment-to-moment technique developed at Space and Naval Warfare Research Centre (SPAWAR) San Diego [9]. The technique simply requires the operator to rate their perceived workload at regular intervals throughout the scenario using a simple 1-7 rating scale implemented in a pop-up window each five minutes. This technique was applied to all operators in the control room.

4.4.2 Situation Awareness

In addition to the moment-to-moment measure, a survey developed at Naval Undersea Warfare Centre, and based on Endsely's Situation Awareness Rating Technique (SART) [10] was also delivered to the control room participants at the completion of the scenario (see Appendix A).

4.5 Simulation Data Recording Plan

The following data and information was recorded during the experiment:

1. Track Data	Track data within the databases of all the Horizon systems was logged every 30s. For each 30s window, the attributes from the last track update were used, unless the track had not been updated during this period, in which case the track was not logged for a second time. Dead reckoned tracks were not recorded.
2. Ground Truth	The ground truth data from the VMSA simulation was recorded every 30s.
3. Mapping Files	Mapping files were recorded across all interfaces where tracks were passed from one system to another. These files map the unique Track Number used by a local system to the unique Track Number of the corresponding track provided by a remote system. These files allow each track within the VBE infrastructure to be mapped back to the corresponding RWO. This is essential for the subsequent analysis.
4. Automated Support	The time and details of alerts and/or recommendations from the association algorithms.
5. Video and Photography	A photographic record and video of the experiment was created.
6. Observer Logs	The observers were required to take appropriate manual logs of the experiment.
7. Horizon Plugin Activation	Horizon plugins activated by the operators to assist in defining role based set-ups for Horizon in future experiments.
8. Display Screen shots	Screen snapshots of the Horizon and ground truth displays were taken every 10 minutes.
9. Workload	Log files from the workload monitoring application.
10. Situation Awareness	SART survey instrument
11. CO Comments	CO was provided with a Dictaphone to record comments on the scenario and usability issues for later correction.

4.6 Participant Briefing

Prior to the experiment the operators were assigned their roles and had their responsibilities explained. They signed consent forms. If they were not familiar with Horizon they were also provided with informal training to allow them to undertake their tasks. Brief details of the scenario were also given to provide the context that would be expected in normal operations.

4.7 Participant Debriefing

Following the experiment the vWaller command team completed the SART (Situational Awareness Rating Technique) questionnaire. SART was developed by the Centre for Human Sciences at Farnborough to provide a subjective estimation of the perceived situation awareness of aircrew. The technique consists of rating items grouped in three principal component dimensions of Understanding, Supply and Demand. The Naval Submarine Medical Research Laboratory in the US adapted the technique to submarine attack centre tasks [7].

5. Analysis of VBE AS-4: Results and Discussion

Our hypothesis was:

> *IF track sharing occurs THEN a more complete and accurate representation of the operating environment can be maintained by each platform.*

This hypothesis speaks to a central assumption that network enabling maritime forces will deliver benefits that will enhance capability. In this study the focus of capability enhancement was the virtual submarine platform. The approach taken here was to address the hypothesis by examining the comparative quality of the picture compiled by networked and non-networked track managers.

5.1 Overview: Picture Quality Assessment

Figure 11 shows ground truth tracks mapping movements of various elements in the scenario. Recall that, in this scenario, only vWaller was unscripted. All other entities were scripted constructed simulations. vWaller was fed tracks (simulated radar detections) from the coalition vessels (FFH1 and FFH2) and from the Unmanned Aerial Vehicle (UAV). Note that the origin of Figure 11 is completely arbitrary. The scale simply indicates kilometres from that origin. These ground truth tracks form the baseline from which all subsequent comparisons were made during later analysis. The key element we are concerned with is vWaller's response to scenario – at the levels of both the human and the overall system response, including developmental automated and part automated subsystems.

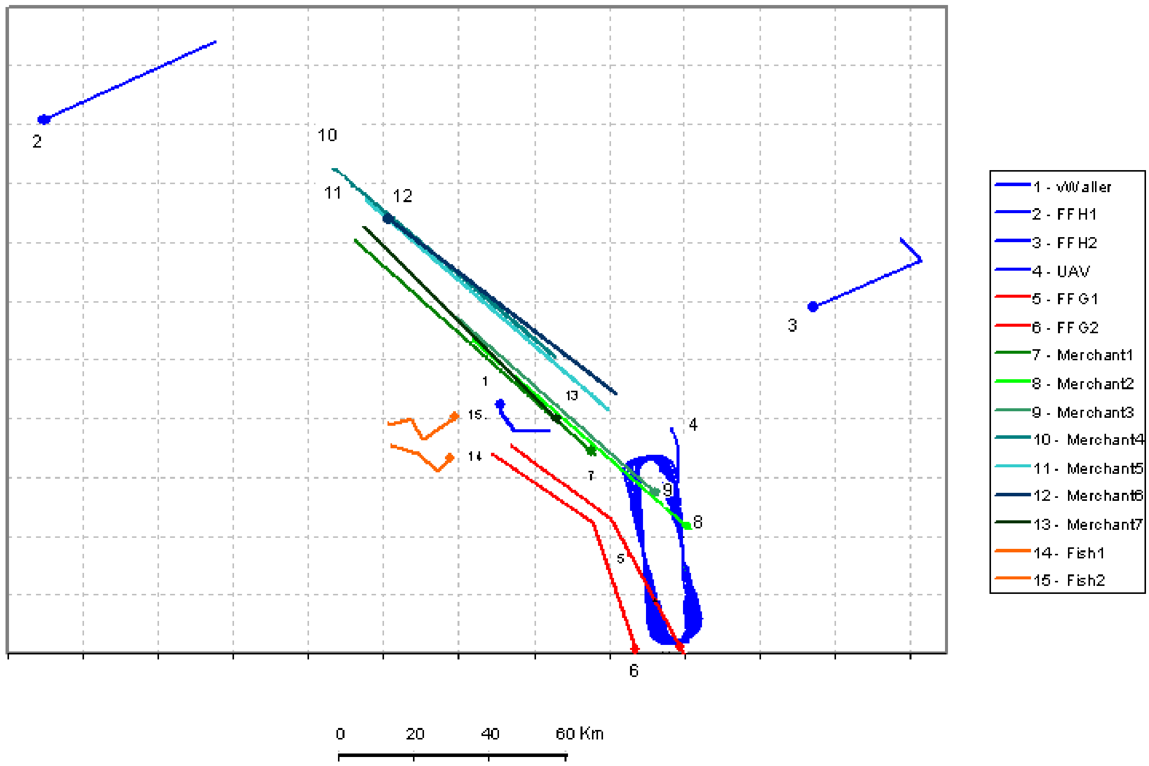


Figure 11 Scenario: Ground Truth tracks during VBE AS4 Scenario

5.1.1 Data analysis support: Tantara

To assist with analysis, Innovation Science was contracted to provide a data processing support tool. This was termed Tantara. Based on Microsoft's EXCEL, Tantara provided an integrated set of data logs and an environment presenting a uniform cluster of operations to be performed upon the VBE AS-4 data set.

5.1.2 An empirical analysis of comparative tactical picture quality for networked vs non-networked picture compilation

As part of the broader VBE process, an evolving set of metrics are being collated and documented. The concept of these metrics has been based upon attributes, identified by the US Single Integrated Air Picture (SIAP) project [9,10], for the assessment of picture quality. Details of these metrics are to be found in Manning & Arulampalam [11]. In this study we chose Completeness, Accuracy and Continuity as the basis of comparison.

5.1.2.1 Completeness

a. Detection Completeness is defined as the percentage of real world objects detected during each 30 second capture of sensor data (In calculating this metric, ownship and coalition partners were ignored).

$$\textbf{Detection Completeness} = \frac{\text{Number of RWOs within picture}}{\text{Total number of RWOs}} \times 100\%$$

The metric can be used to compare the relative completeness of the Tactical Picture compiled at each Track Manager Display. Since this metric assesses detection of RWOs, it was appropriate that the Track Manager working display (where raw detections are registered) rather than the Tactical Plan Display (onto which tracks are promoted) be used.

Figure 12 shows the Detection Completeness metric plotted at each 30 second data capture point taken during the scenario. The figure gives a general indication of the advantage of track sharing for detection. The two network capable pictures (Net TM and Trials TM) registered a greater percentage of possible detections overall than Ownship (OSTM) tactical picture.

It appears that the greatest advantage of track sharing arises early in the scenario (as previously noted in VBE AS-2). Some 50 - 70% more detections were registered at the Net TM and Trial TM displays. At this level there was little difference between the Net TM and Trial TM displays. The overall reduction of Detection Completeness particularly towards the later part of the scenario is probably due to the movement of a large proportion of the contacts toward the Northwest. In the later stages of the scenario, vWaller was evidently able to hold a greater proportion of new contacts entering its sensor range.

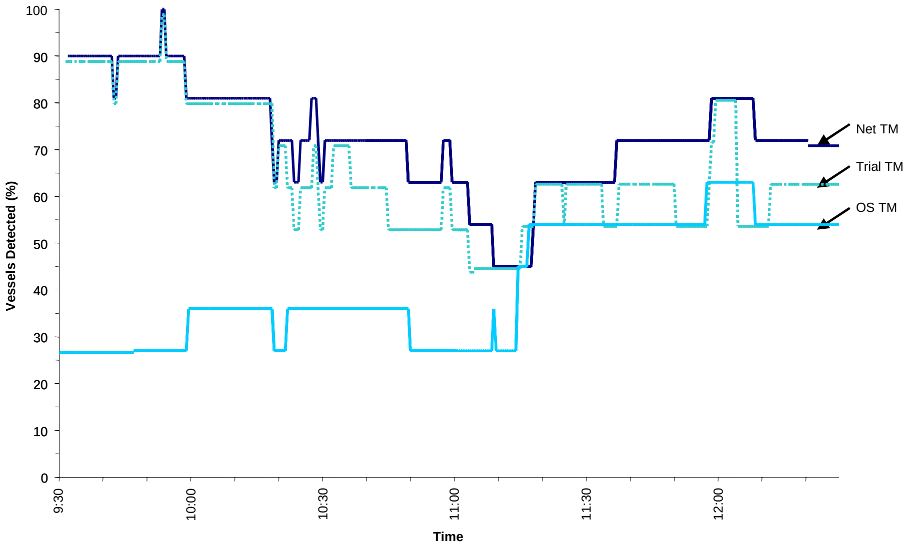


Figure 12 Comparison of Detection Completeness at each Picture Compilation process

b. Solution Completeness is defined as the percentage of real world objects with position solutions. In calculating this metric, ownship and coalition partners were ignored.

$$\textbf{Solution Completeness} = \frac{\text{Number of RWOs within picture with position solutions}}{\text{Total number of RWOs}} \times 100\%$$

Plotting this metric (see Figure 13) reveals that the network enabled Track Managers (Net TM and Trials TM) were able to generate solutions for between 20% to 40% more of the RWOs detected throughout the simulation. The output of the metric is plotted in Figure 13. This graph compares the TPD (Display onto which promoted tracks are displayed) of each track manager. Recall that the TPD is the product of track promotion. Hence, it was intended that it include the operator's best estimate of the position of elements in the tactical picture. Note that at about 10:00, the picture compiled at the Net TPD appears to have suffered from some short-term problem in generating solutions. It is not clear at this stage precisely what caused this to arise. However, some of the difficulties faced by the Net TM will be discussed in detail later.

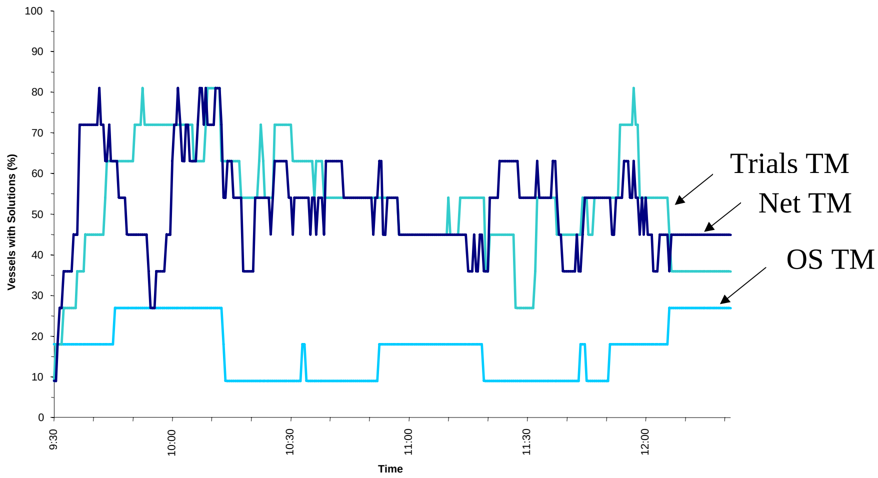


Figure 13 Solution Completeness in Picture Compilation: Tactical Picture Display Comparison

Comparison of networked and non-networked picture compilation completion at the Track Manager working display is shown in Figure 14. The Net TM and Trials TM Displays appear to have been quite similar in holding contacts with solutions. OS TM held between 40 and 70% less vessels with solutions.

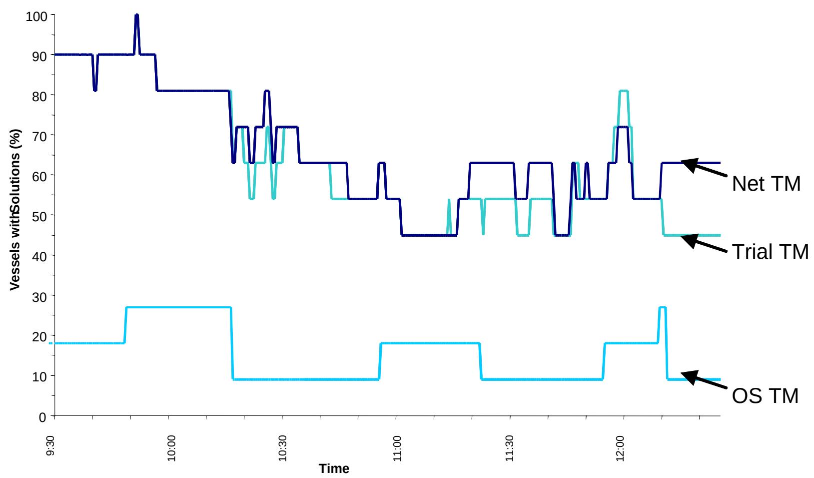
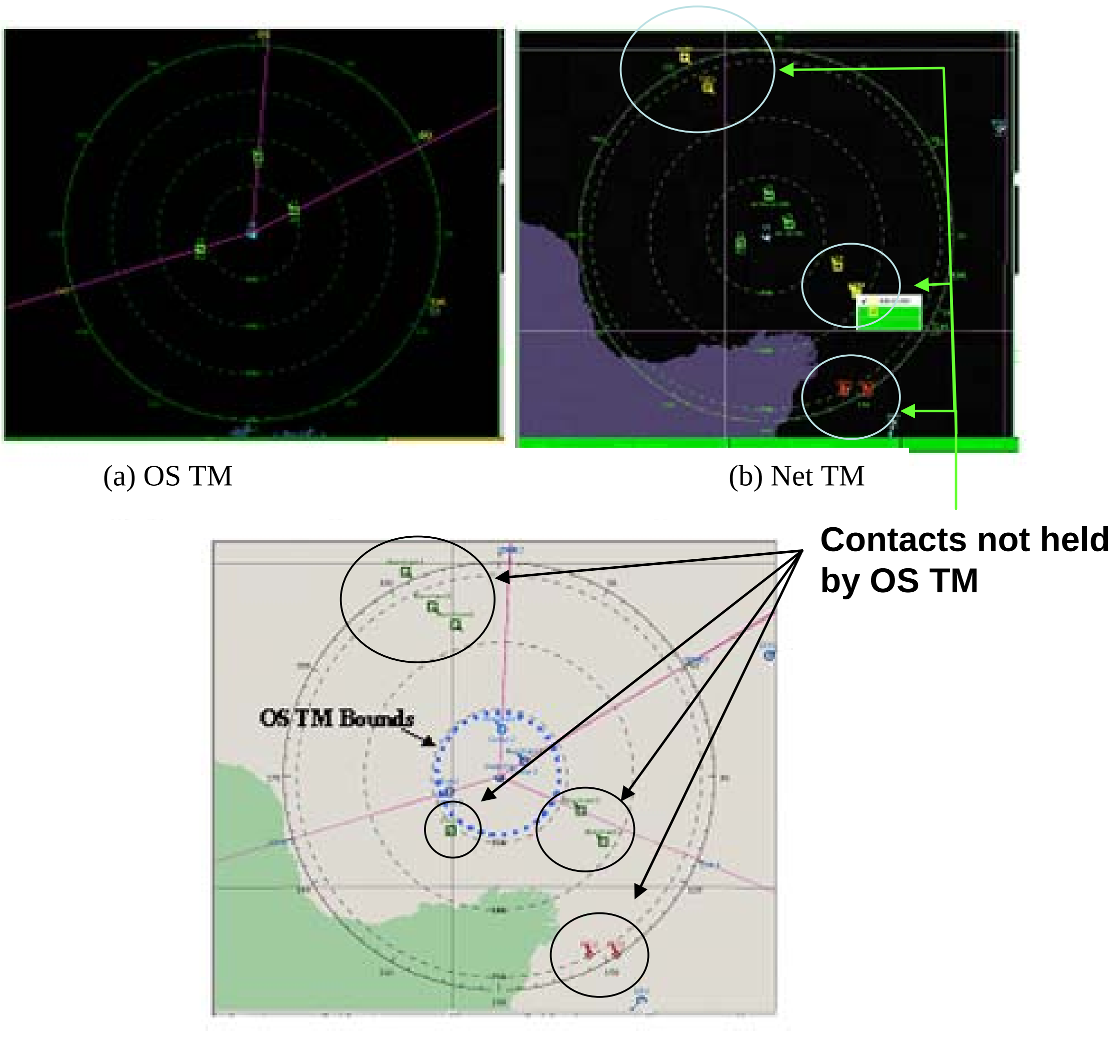


Figure 14 Solution Completeness in Picture Compilation: Track Manager Display Comparison

These findings are not altogether surprising given the larger number and distribution of sensors accessible by the networked track management operators. In terms of the tactical advantage of this enhanced picture completeness, several screen captures from the scenario are revealing. For example, in Figure 15a the OS TM display reveals only two contacts, while the Net TM display, Figure 15b shows considerably more contacts and in particular it shows hostile vessels approaching from the South South-East of vWaller. As a final demonstration of the extended field of view of the networked capable picture, a ground truth display is shown in Figure 15c. The central dotted circle signifies ownship sensor ranges while networked displays were capable of holding all contacts outside of that small field of view.



(a) OS TM

(b) Net TM

(c) Ground Truth

Figure 15 Comparison of Tactical Pictures taken at 10.13am

5.1.2.2 Accuracy

Another attribute of picture quality deemed important was the difference between estimated position and ground truth or **Position Error (PE)**. The position error was the difference between the solution for any given track compared to the true position of the relevant RWO

(clearly, care has to be taken as to the appropriate use of this metric for tracks that are the result of incorrect association).

$$\mathrm{PE} = \sqrt{(\hat{x}_k - x_k)^2 + (\hat{y}_k - y_k)^2}$$

where (x_k, y_k) is the simulation coordinate position of an RWO and (x_k, y_k) is the estimated solution of the RWO.

As an initial description of what this metric describes, Figure 16 compares the position error for both the TMA and Ownship solutions for Merchant 1. This contact held constant speed on a constant course throughout. The two curves are intimately related since the OS TM receives TMA output over time as a refinement of contact solutions. Note that for both curves, error is initially quite large and unstable (between 500 to 5200 meters compared to ground truth). However, position-error stabilises and is minimised during the first 25 minutes of the scenario. The initial error arises as the TMA operator 'stacks the dots' on the TMA screen (manually minimises residual error in localisation).

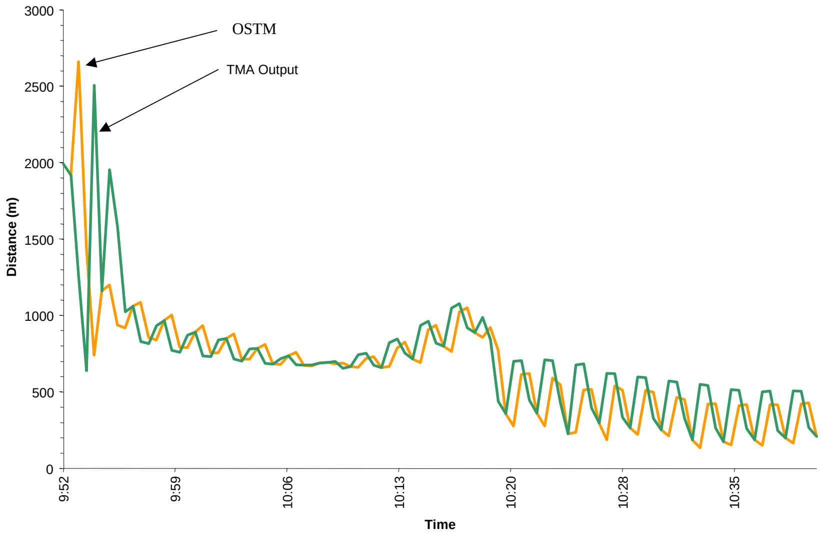


Figure 16 Positional Error for an example contact: Merchant 1 (Ownship Track Manager)

Note that the tracks generated at the Net TM and Trials TM displays are derived from a number of different sensor sources. To demonstrate the role of each sensor in the sharing of tracks, Figure 17 shows the contribution of each sensor as a timeline. Ownship sonar held this particular contact for approximately 1/3 of the scenario. Several passes of the UAV and the coalition vessels held the contact longer.

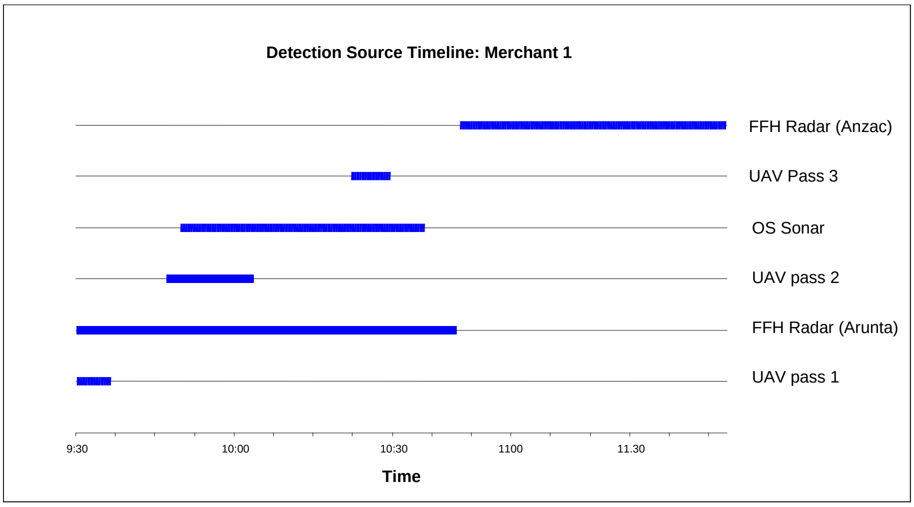


Figure 17 A timeline of sensor detection for an example contact: Merchant 1

While Figure 17 shows the how different sensors detected a particular vessel Figure 18 demonstrates the manner in which the input of these same sensors was managed, that is, sensor output tracks associated and the impact of track fusion upon the estimated position of this Merchant Vessel at any particular instant (in this case estimation error has been plotted).

In Figure 18 each coloured line represents a different sensor (or constructed platform). Clearly, a major task for the networked operators was to manage constituent tracks appropriately, that is, to associate together the tracks emerging to optimise the solution (minimise solution error). For example, in the case of Merchant 1, Sensors included Ownship (OS) Sonar, UAV radar tracks and coalition radar sensors (all 'federate' models). Separate fusion actions can be seen where the separate lines merge. Four of the major fusion actions involving this track are shown. Note that fusion at times actually increased error relative to ground truth with a subsequent improvement in error. Some means of filtering initial error generated by or associations maybe useful – such as a simple error-bounding filter. The position error shows much about the challenges facing tracking in an NCW operational environment.

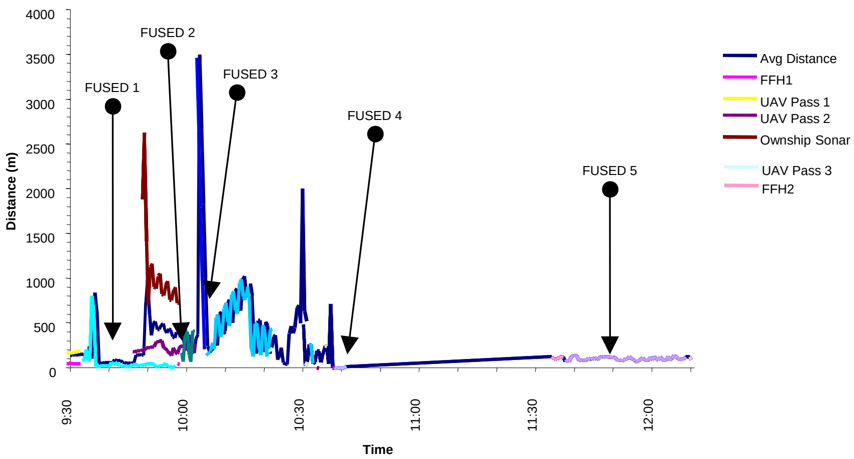


Figure 18 Subcomponents of position error for an example contact: Merchant 1

Figure 18 suggests that fusion of tracks from different sensor sources did not necessarily reduce the error in localisation. There appears to have been difficulty fusing tracks derived from coalition sensors with ownship data. For example, the sector in the error curve for contact Merchant 1 increases dramatically for the constituent track that comprised Ownship detection of contact from Sonar 3. Indeed error seemed to spike to peak at 3,500 m (at about 10:06).

Given that some interesting errors did arise in localisation and tracking of certain contacts using track fusion, it is useful to directly compare the average position error for some other example tracks generated at each picture compilation operator.

Figure 19 below compares the average positional error across all sensors for the contact Merchant 1 at each of the Track Manager Tactical Picture Display. Note firstly that there is substantial variability in errors generated at the level of Ownship TMA solutions. This error reduces from about 1500 m to below 1000 m then to below 500 m as the Merchant vessel transits through sonar range.

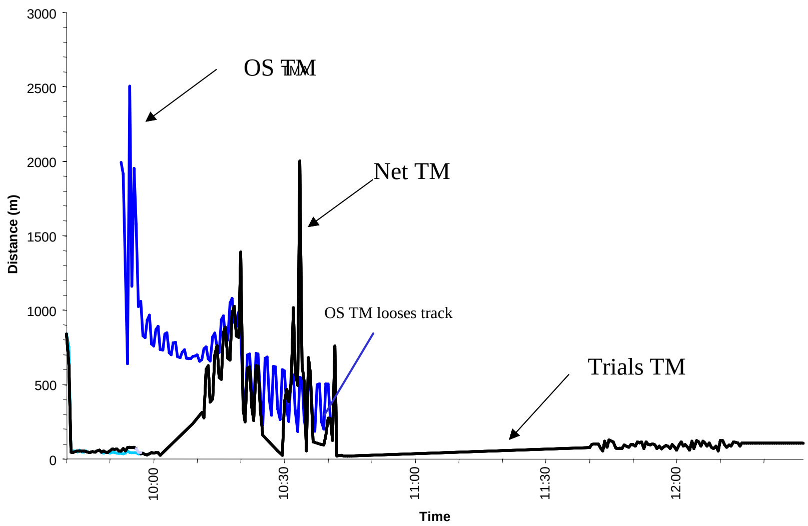


Figure 19 Average position error for an example contact: Merchant 1

In the example of Merchant Vessel 2 (see Figure 20), a somewhat different pattern emerges. Once again, the overall value of networking is clear from the small proportion of time that Ownship sensors hold the contact. The Trials TPD also appears to consistently hold the vessel with limited error throughout the scenario as the Merchant 2 tracks North East past vWaller's position. The Net TPD, however appears to have a problem with some dramatic error values. A single inconsistent data point places the average error in position well beyond 3,000 m. Several other spikes in error also emerge. This kind of error is difficult to explain. Such error could be filtered by constraining the rate of change in location of a fused track according to realistic motion rules. It appears to be a possible risk for the NCW capability that unpredictable errors can emerge in track management due to perturbation of data aggregation tools such as the fusion algorithms used.

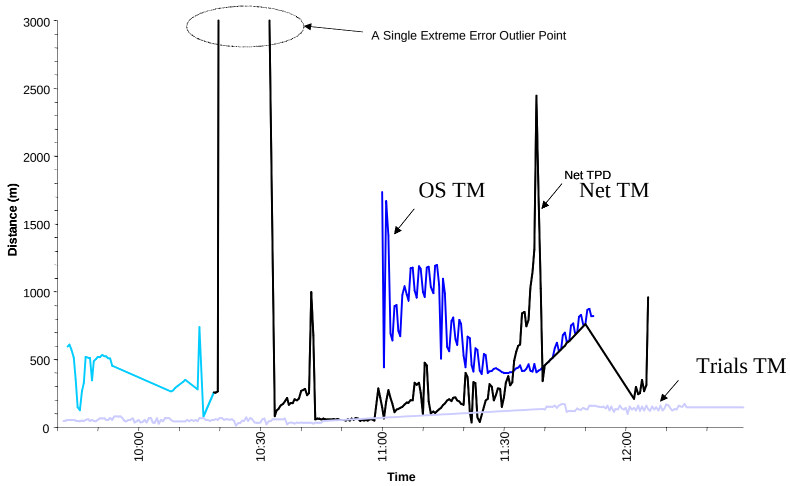


Figure 20 Components of average position error for an example contact: Merchant 2

Similarly, in the case of priority contacts, FFG1 and FFG2 (hostile Frigates) there are benefits evident in the latency of detection and tracking contacts during the scenario (see Fig 21 and 22). In Figure 21 the Net TPD plot of position error is markedly more stable than that for the Trials TPD. The Trials TPD held the track for FFG1 in excess of 3000 m from its actual position and for a period of over an hour. Even so, ownship TMA only tracked the vessel for a very small proportion of the actual scenario (ownship TMA). Once again this points to potential risks inherent in the management of tracks made up of multiple components. It is also possible that the level of increase of information may have led to instability because the solution space is larger. At this stage it is difficult to clarify that possibility.

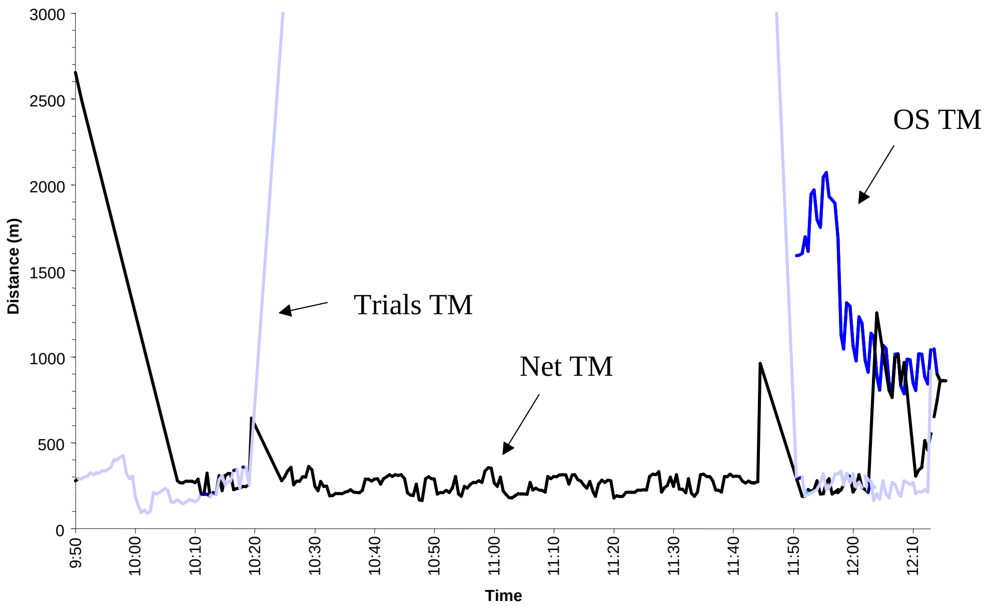


Figure 21 Errors for each networked picture for priority contact FFG1 (hostile Frigate)

Finally, in this series of examples, Figure 22 plots the average position error for the other hostile Frigate – FFG2. Once again, the vessel was not detected by vWaller until the simulation was almost over. Detections comprising the contact FFG2 until about 11:55 (when Ownship

sonar detections were initiated) were from offboard sensors only. It also appears that the relative accuracy of Ownship TMA can represent a limiting factor upon the subsequent accuracy of fused or associated tracks simply because the error distance was greater for Ownship sonar detection.

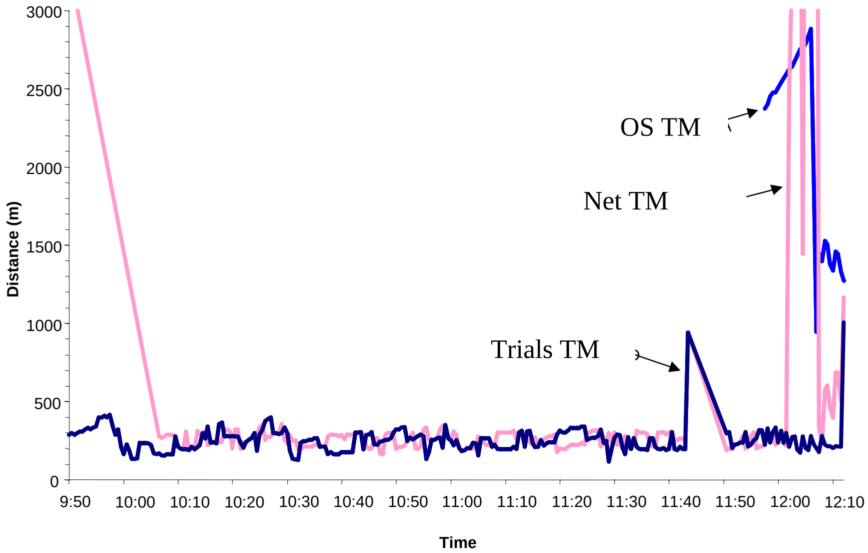


Figure 22 Components of average position error for priority contact FFG2 (hostile Frigate)

The pattern of errors above indicates some of the potentially difficult aspects of track management in NCW operations. Particularly when fusion is initiated, it can be anticipated that errors will be large. From our evidence, it takes time for error to "normalise".

These sources of error should not be over-stated. In the bigger picture, things were not as unpredictable as these chosen examples suggest. As the entire scenario unfolded, Figure 23 demonstrates most RWO solutions (i.e. 60 – 90 %) fell within 3000m of ground truth. This metric differs from that above in that it provides an indication of the overall accuracy of all tracks with solutions. This distance was nominally set to 3km as a typical search area for a torpedo. In calculating this metric the detection of own ship and coalition partners are ignored. The metric used to describe this characteristic of the situation is as follows, where PROW is the percentage of ROWs with a solution within x kilometres of its true position:

$$\text{PROW} = \frac{\text{Number of tracks with a positional error less than x km}}{\text{Total number of detected tracks with solutions}} \times 100\%$$

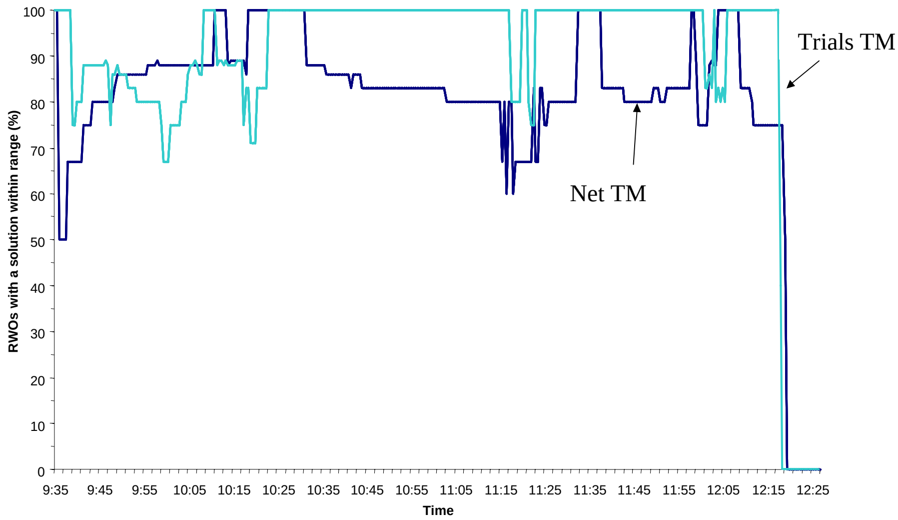


Figure 23 RWOs with a solution that is within 3000m of ground truth

The range of 3000m selected here is probably reasonable for distant contacts. However, when contacts are high priority or dangerous then obviously the range may not be appropriate.

5.1.3 Continuity of Tracking

Figure 24 below outlines the result of applying the Detection Continuity metric for each track in the scenario at each Track Manager.

Detection Continuity (DC) is defined as the total duration a given RWO (eg. Merchant 1, 2 etc) is detected, expressed as a percentage of the total scenario duration,

$$DC = \frac{\text{Duration RWO is detected}}{\text{Duration of scenario}} \times 100\% .$$

Clearly, the Net TM and Trials TM have held detection for most contacts for longer duration in this scenario. In particular, the priority contacts (hostile FFG1 and FFG2) were held with greater continuity when tracks were shared between coalition vessels (between 30 % - 60% longer). This finding is scenario dependent since the hostile Frigates approached the range of vWallers's sensors only in the last half-hour of the scenario.

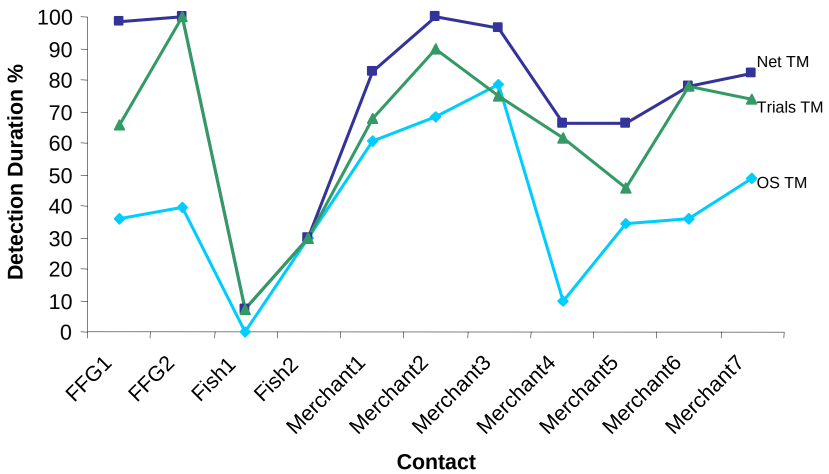


Figure 24 Comparison of track continuity between Track Managers

Next, considering the relative advantage of networking for track continuity, Figure 25 below plots the continuity for each individual sensor platform in the coalition. This is compared to a plot of the continuity metric for the entire coalition. The figure therefore describes an enhancement of tracking continuity due to sharing of sensor data within the coalition. The network adds to the overall continuity of tracking.

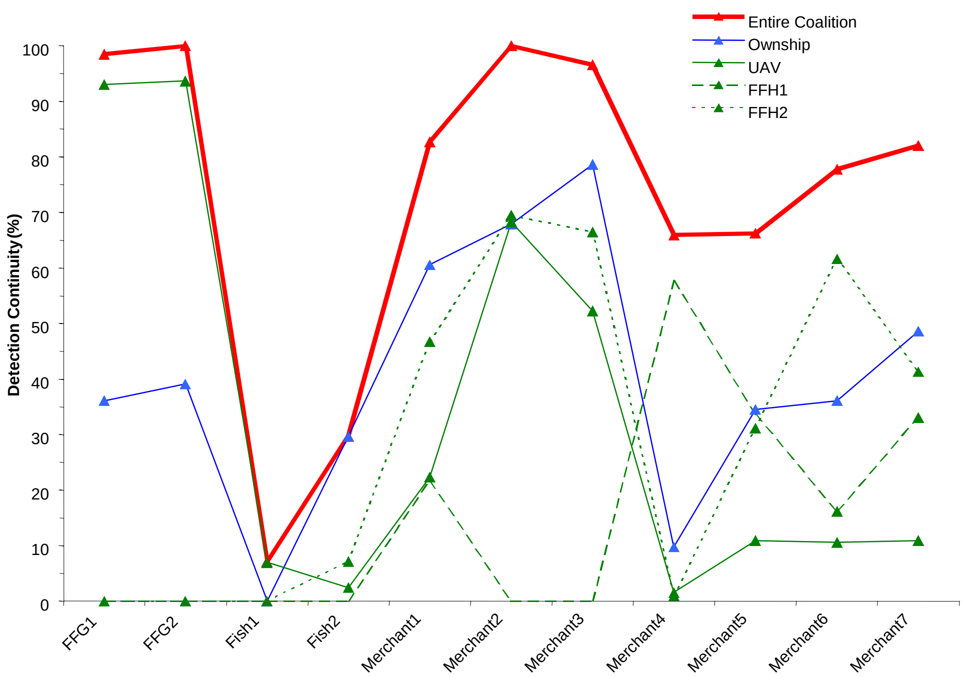


Figure 25 Detection continuity across coalition sensor elements for each contact in the scenario

In summary then, our evidence supports the first hypothesis: that track sharing would facilitate a more complete and accurate tactical picture. This was primarily because track sharing essentially extended the effective sensor range of the submarine relative to its onboard

sensors. The networked picture displayed entities that vWaller's organic sensors simply could not detect. This enabled the networked picture compilation process to access distant contacts sooner and to track those contacts with greater continuity than other was feasible for picture compilation dependent solely on ownship sensors.

5.2 Priority Target Tracking

5.2.1 A second hypothesis addressed was the following:

IF track sharing of high priority targets occurs THEN they can be more continuously monitored with greater accuracy.

This second hypothesis concerns high priority targets. In this scenario the priority contacts were FFG1 and FFG2. These vessels were hostile contacts. Figure 26 is meant to summarise the impact of track sharing within the coalition. The Figure plots the percentage enhancement in continuity achieved by networking platforms compared to ownship detection for each contact.

Track sharing has therefore, on our evidence, enhanced the continuity of detection for the two priority hostile FFGs.

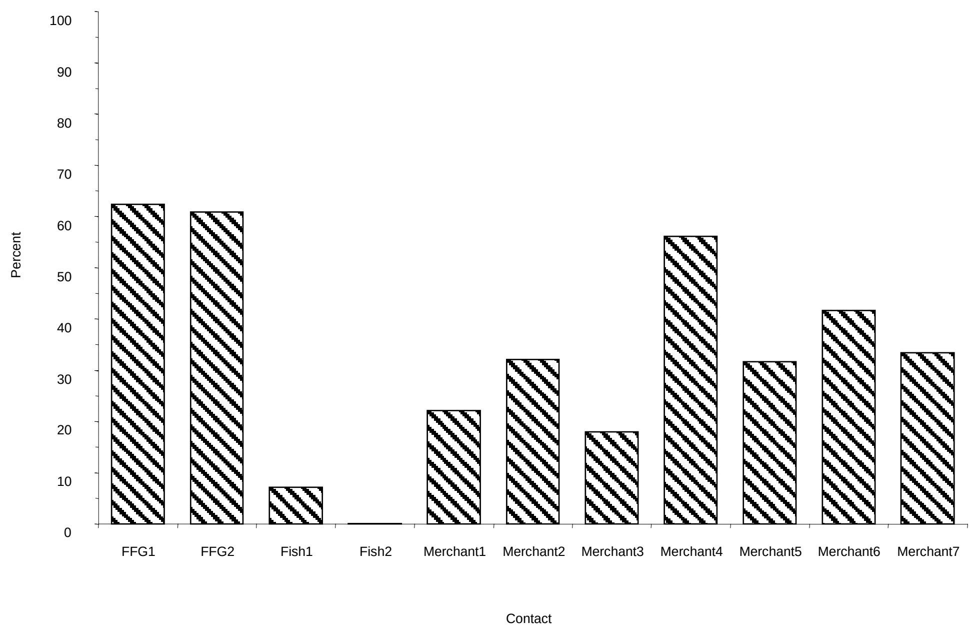


Figure 26 Percentage increase in detection continuity achieved by networking(for each contact)

Although the above figure demonstrates the increase in detection continuity associated with track sharing it can not indicate whether or not this has actually been of any operational benefit. Determining this is especially difficult in scenarios that are limited to general surveillance activities. The observation that tracks sourced from the coalition detected and held enemy vessels (with low error) several hours prior to ownship sonar tracking does

suggest that the Commander would have had much longer to deal with the enemy approach[3]. Once again, we cannot claim that this improves his situation tactically.

5.3 Area of Uncertainty

Our third hypothesis examined was the following:

IF shared tracks have a realistic Area of Uncertainty THEN command will have a greater trust in the information and will associate and fuse them more readily with own ship tracks.

This hypothesis concerns the exploratory development and representation of an area of uncertainty for the estimated positions of contacts.

Area of Uncertainty (AOU) Accuracy is defined as the percentage of real world objects lying within the estimated target uncertainty area for their corresponding tracks. The target uncertainty area for a particular track is determined by the track estimate, its covariance, and a confidence level which gives the probability that the true object lies within the uncertainty region. In calculating this metric, ownship and coalition partners were ignored. To define this metric, let

$$T_i = \text{True position of RWO corresponding to track } i$$
$$A_i = \text{AOU corresponding to track } i$$
$$N = \text{Number of detected RWO with solutions}$$

and let $\mathrm{I}(T_i, A_i)$ be an indicator function given by

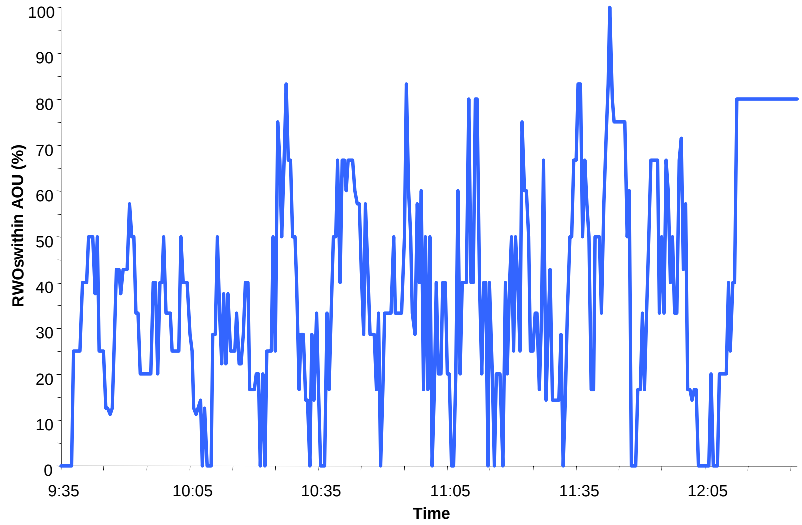
$$\mathrm{I}(T_i, A_i) = \begin{cases} 1, & T_i \in A_i \\ 0, & \textit{otherwise} \end{cases}$$

Then, the AOU Accuracy can be defined as

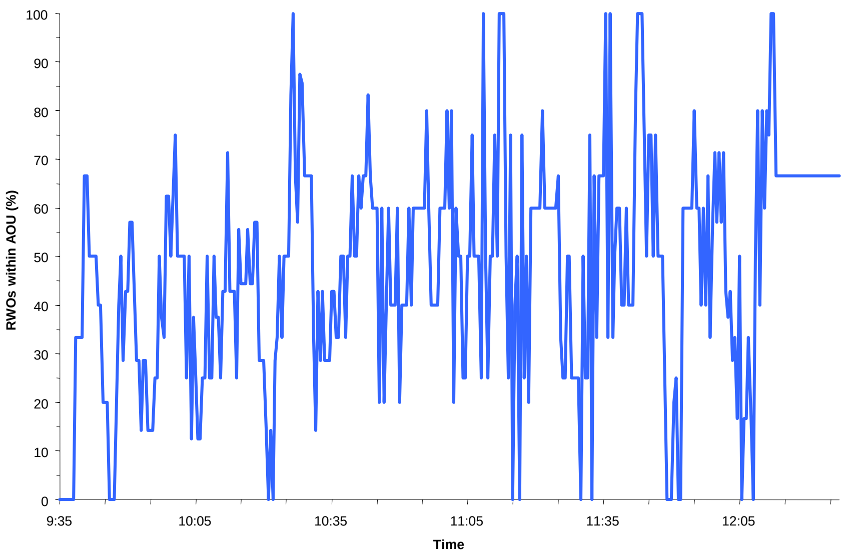
$$\text{AOU Accuracy} = \frac{1}{N}\left(\sum_{i=1}^{N} \mathrm{I}(T_i, A_i)\right) \times 100\%$$

A great deal of fluctuation was evident in the AOU accuracy results. Figure 29 below is a good example of this. It illustrates the percentage of Real World Objects within their actual AOU for both the Net TPD and Trials TPD track data. The percentage of contacts that actually fell within their AOU varied dramatically and this probably meant that AOUs were not useful, that the AOUs were too small, or that the variability of positions was too great.

[3] Indeed the CO did claim that the biggest advantage he saw in sharing tracks was that they informed him of the nature of low-bearing rate (very distant) contacts.



a. Net TPD



b. Trials TPD

Figure 27 Percentage of vessels (RWO) falling within calculated AOU for vessels tracked in Networked picture compilation

Observation of the operators during the simulation run saw no use of the available AOU display at all. We cannot really comment on the hypothesis posed to address the question of trust in the positioning of vessels for this scenario.

5.4 Human Performance Factors

5.4.1 Workload

5.4.1.1 Moment to moment

As a guide to the workload to which the operators were subjected, a simple moment-to-moment workload measure was carried out. This involved a pop-up screen containing a rating scale (1 = low to 7 = high).

The findings for this measure are shown in Figure 28. The figure suggests that the NetTM (Networked track manager) perceived himself to be under quite a high workload in comparison to the other operators. Both Ownship and Trials TM indicated that their workload was very low. Given that the Net TM and Trials TM tasks were very similar, one possible explanation for the difference in their perceived workload might be involvement of the CO with Net TM Picture Compilation. The cognitive effort of paying attention to the CO in discussing the picture layout may have meant that perceived workload was high.

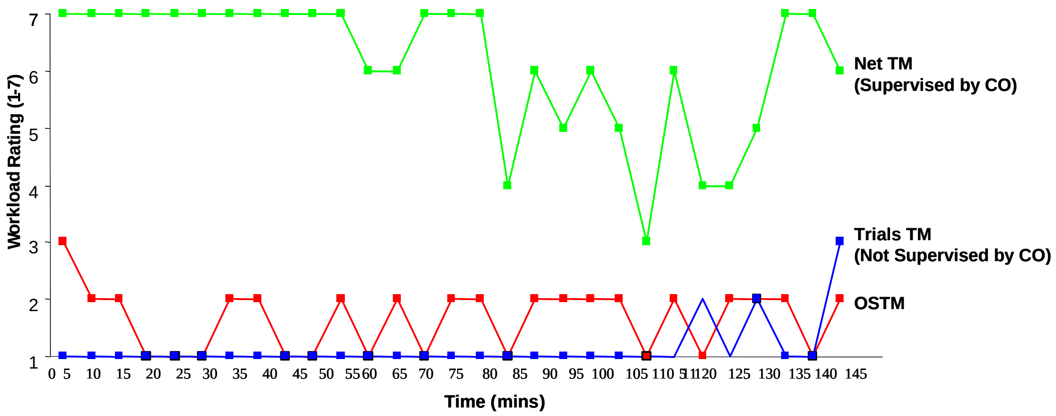


Figure 28 Moment-to-moment subjective workload

5.4.1.2 Situation Awareness Rating Technique

The SART scores taken after the simulation was run are shown in Figure 29. Participants in the study appear to have felt that they understood the situation quite well. They also believed they had sufficient resources with which to deal with the situation. Interestingly, the OS TM whose focus was upon his ownship sensors believed his understanding of the situation was high. That is quite possible, however, relative to the other TMs, his field of view was small.

The degree that participants found the tasks they performed to be demanding suggests that all participants thought the scenario did not challenge them. Only the Net TM rated Cognitive Demand as moderate.

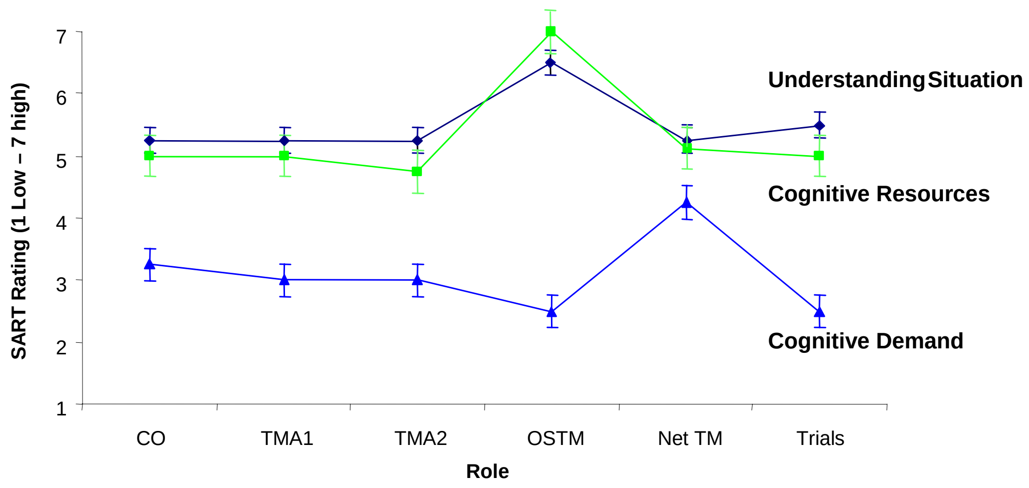


Figure 29 Situation Awareness Rating Technique Scores (Showing Standard Error Bar)

6. Concluding Remarks

6.1 General Conclusions

In conclusion, the simulation supporting VBE AS-4 ran smoothly. The RAN staff employed to conduct picture compilation and to simulate control room activities were largely engrossed in the task at hand suggesting that efforts in immersing them in a realistic setting were fruitful. It appears that the surveillance task faced by vWaller was a fair representation of the type of task faced at sea.

6.1.1 Tactical picture quality in a networked conventional submarine

To examine tactical picture compilation three hypotheses were considered:

1. IF track sharing occurs THEN a more complete and accurate representation of the operating environment can be maintained by each platform.
2. IF track sharing of high priority targets occurs THEN they can be more continuously monitored with greater accuracy.
3. If shared tracks have a realistic Area of Uncertainty THEN command will have a greater trust in the information and will associate and fuse them more readily with own ship tracks.

The evidence from this VBE study substantively supports hypotheses 1 and 2. This is largely due, it would appear, to the increased 'field of view' or sensor range that is likely to be associated with NCW in the maritime domain. Considerable picture quality benefits do seem to have emerged for networked track managers. It should be noted that we have only anecdotal evidence that this finding means that there were tactical benefits for the CO of the virtual submarine. VBE AS-4 was not designed to establish that possibility. Regarding the

third hypothesis, we have found that the CO paid no attention to the AOU functionality available and therefore we can not support that hypothesis. Given the variability of the AOU representation this is probably not surprising. A more rigorous exploration of the issue may shed light on the most appropriate means of exploiting visualisation to emphasise the uncertainty inherent in track management.

6.2 Operator Performance

In this study we did not find a great deal of difference between the two networked operators except in their workload. One possible reason for this is that the scenario was at a tempo so low as to fail to generate the sort of stress that one might expect in a wargame. Once the work of picture compilation becomes more hectic then there is a good chance that operators will rely on the assistance of automation to cope.

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Appendix A: SART Questionnaire

The following questionnaire forms the basis of the Situational Awareness Rating Technique (SART) developed in the UK. SART uses subjective estimates of personal and task-dependent factors which affect task performance and understanding to measure Situation Awareness. Situation Awareness refers to your ability to relate the meaning of events and elements in a noisy, uncertain environment to mission goals and objectives. The technique involves the scoring of fourteen different scales, each of which is potentially a factor in your Situation Awareness.

Each different category should be rated on a scale from a low of one to a high of seven. These values are a subjective measure of your individual perceptions during the VBE. There is no right or wrong answer to give, only your best estimate of your personal experience from the point of view of your assigned role. Do not spend too much time on any one item. Your initial 'gut feeling' is likely to be the most accurate estimation.

The questionnaires should be completed individually, but you may ask for further explanation of any of the categories.

1. Demand on Cognitive Resources

How demanding was the exercise on your cognitive resources? Were there many difficult decisions and situations demanding constant attention and maximum efforts (high) or was it easy and minimally demanding (low)? In other words, how much did your brain hurt?

Score ☐ **1 (Low)** **7 (High)**

2. Instability of Situations

How changeable were the situations and environmental factors encountered through the course of the exercise? Were they very dynamic and likely to change suddenly (**high**), or were most of them slow and stable with easily predictable outcomes (**low**)?

Score ☐ **1 (Low)** **7 (High)**

3. Complexity of Situations

How complicated were the situations? Were they complex with many interrelated components and phases (**high**), or were most simple and straight forward (**low**)?

Score ☐ **1 (Low)** **7 (High)**

4. Variability of Situations

How many elements were changing at any one time in a given situation? Were there a large number of dynamic variables (**high**), or very few that might change at once (**low**)?

Score ☐ **1 (Low)** **7 (High)**

5. Supply of Cognitive Resources

How great a supply of cognitive and attentional resources coupled with decision aids and analysis tools did you have for problem-solving, decision-making, and other functions during the exercise? Could you bring a very large capacity to bear on the problems (**high**), or did you have limited resources at your disposal in each situation (**low**)? In other words, did you have the assistance and resources you required either from other operators or computers to help make decisions and perform your job to the required level?

Score ☐ **1 (Low)** **7 (High)**

6. Readiness

How alert and ready for action did you feel throughout the course of the exercise? Could you anticipate the flow of events and respond quickly (**high**), or were you hard pressed to keep up with evolving situations (**low**)?

Score ☐ **1 (Low)** **7 (High)**

7. Concentration of Attention

How much could you concentrate your attention in each problem situation? Were you always focused on important elements and events (**high**), or did technical details, controls, and displays distract you and draw your attention elsewhere (**low**)?

Score ☐ **1 (Low)** **7 (High)**

8. Division of Attention

Were you able to divide your attention among several key issues in the course of the exercise? Were you usually concerned with many aspects of current and future events simultaneously (**high**), or did you focus on only one thing at a time (**low**)?

Score ☐ **1 (Low)** ______ **7 (High)**

9. Spare Mental Capacity

How much mental capacity did you have to spare in this exercise? Do you think you could have dealt with a significant number of additional elements and variables if necessary (**high**), or did the complexity of the exercise take all your mental capacity (**low**)?

Score ☐ **1 (Low)** ______ **7 (High)**

10. Understanding the Situation

How well did you understand the environment, the tactical situations, the problems, and tasks presented in the exercise just run? Include ownship, all contacts, and all sources of information, as well as mission goals, strategy, and tactics for this purpose. In retrospect, did you usually have a good understanding in most cases (**high**), or did you have many unknowns and uncertainty a major part of the time (**low**)?

Score ☐ **1 (Low)** ______ **7 (High)**

11. Information Quantity

How much useful information were you able to obtain from all available sources in the exercise? Did you receive and understand a great deal of pertinent data (**high**), or was very little of the information of much use for your task at hand (**low**)?

Score ☐ **1 (Low)** ______ **7 (High)**

12. Information Quality

How good was the information you obtained about the situation? Was the knowledge communicated via all sources very accurate and precise (high), or was it noisy with high levels of uncertainty (low)?

Score ☐ **1 (Low)** ______ **7 (High)**

13. Familiarity with the Environment

How familiar were you with the different elements and events in the environment and situations encountered during the course of the exercise? Could you call on a great deal of relevant experience and knowledge to fill in gaps in the available information (**high**), or did you find significant aspects of the exercise new and unfamiliar to you (**low**)?

Score ☐ **1 (Low)** ________ **7 (High)**

14. Situation Awareness

Evaluate your awareness of the overall meaning of events and elements in the environment to the mission objectives. Did you always have a complete picture and a plan for how the various elements would affect the mission and could you anticipate future mission-critical events and decisions well in advance (high), or did you have very limited ability to predict the impact of on-going activity on future events and overall mission goals (low)?

Score ☐ **1 (Low)** ________ **7 (High)**

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19. ABSTRACT

This report provides a summary of Virtual Battle Experiment-AS4 held at DSTO-Edinburgh in August 2003 in support of TTCP MAR TP-1 (Command, Control and Information Management). The study was designed to investigate possible picture compilation benefits provided by a maritime tactical network. Novel human-in-the-loop simulation methodology was employed in which a networked virtual submarine undertook a surveillance patrol with track information fed to three separate Track Managers. Data analyses compared resulting picture quality and human performance. The findings of the study were that networking assisted picture completeness and detection continuity at the cost of higher operator workload

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